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TRANSISTOR FUNDAMENTALS

A PROGRAMMED LEARNING COURSE

VOL. 1 BASIC SEMICONDUCTOR and CIRCUIT PRINCIPLES

by Robert J. Brite

Under the direction of Training & Retraining, Inc.

TRI

Transistor Fundamentals

Volume 1

Basic Semiconductor and Circuit Principles

by

ROBERT J. BRITE

Under the direction of

Training & Retraining, Inc.

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Preface

In 1948 the transistor was announced. Less than 10 years later it had supplemented the vacuum tube in most electronic circuits. A decade after that we find that the transistor is replacing the vacuum tube in electronics. In those 20 years there has not been one attempt to change the approach to the teaching of electronics. The system remains the same: teach basic electricity, then vacuum tubes, then electronic circuits, and finally introduce the concept of the transistor by comparing it to vacuum-tube operation.

Why should a device like the vacuum tube that is becoming obsolete be used as the major vehicle for explaining electronics? The answer must be "tradition." This series breaks with tradition and faces the real world—the world of semiconductor electronics. Immediately, in the first volume of the series, semiconductor theory is introduced with the study of basic electricity. The second volume finds basic transistor circuits as the major topic of discussion. Volume three goes through radio and television solid-state circuits and finally, in volume four, digital circuits are explored. The result is a true *transistor* series.

The material is presented so that the student will gain a firm background in "solid-state" electronics, including troubleshooting techniques. This, coupled with the unique modified linear-programming technique, makes this a complete *self-instructional* course. The summary questions and answers at the end of each chapter and the final examination allow the student to check his progress and understanding of the material.

TRAINING & RETRAINING, INC.

ABOUT THE AUTHOR

Robert J. Brite is currently Data Manager for ITT Defense Communications, in Nutley, New Jersey. He studied engineering at Monmouth College and the Cooper Union for the Advancement of Science and Art. His electronics career dates back to 1949 when he was a troubleshooter for a major television manufacturer. His background includes: teaching radar for the Signal School at Fort Monmouth; field engineering in both radar and computer fields; and writing in the area of computers, missile guidance, communications, and electronic training devices. A two year stint at the Kilmer Job Corps Center has been his most challenging and rewarding experience. Serving in the capacities of Director of the Reception Center and Management Development Coordinator, he was one of the pioneers in the development of the unique techniques employed to wage the war on poverty. He was a member of the visitors and speakers bureau at the center and has appeared as a guest chairman and moderator for the Society of Technical Writers and Publishers. He is coauthor of *Basic Electricity and Electronics*, a five-volume programmed learning course, as well as *Synchros and Servos*. Mr. Brite has also been editorial and technical consultant for the various volumes of the Space Technology Series also published by Howard W. Sams & Co., Inc.

Acknowledgments

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In this regard, prime consideration is given to Robert J. Brite, Data Manager for International Telephone and Telegraph Defense Communications Division. The selection of the content of the volumes, the initial preparation and organizational work, the writing contributions across the board, editing and final review, and the finalization as to technical content and educational value are due principally to his tireless and conscientious effort.

Credit for the initial concept of the programmed learning technique goes to Stanley B. Schiffman, staff member of Training & Retraining, Inc.

Finally, special thanks are due to the publisher's editorial staff for invaluable assistance beyond the normal publisher-author relationship.

SEYMOUR D. USLAN, Editor-in-Chief
and
HERMAN SCHIFFMAN, President
Training & Retraining, Inc.

Introduction

This book carefully explains the principles of basic electrical circuits and those of semiconductors. Following a unique method of presentation these principles are related through simple analogies to devices with which you are familiar. This volume first supplies the building blocks necessary for progressing to the more complex materials presented toward the end of the volume and the material found in the subsequent volumes of the series. The constant reviewing and application of the material presented in this book will give the student the background that will allow him to proceed through the remainder of the series.

WHAT YOU WILL LEARN

The book begins with an introduction to the transistor and immediately offers the student a firm understanding of voltage and current. The next chapter contains a detailed explanation of resistance and its effect on current and voltage and presents the student with the manipulation of Ohm's and Kirchhoff's laws. A chapter entirely devoted to semiconductor principles prepares the student for the next volume on transistor circuits. The volume ends with a detailed study of the nature of inductance, capacitance, and resistance in a-c circuits.

WHAT YOU SHOULD KNOW BEFORE YOU START

The only requirements for studying this series are a firm background in simple mathematical techniques, including powers of ten, basic algebra, and trigonometry (a review

of this is offered in this volume). For the most part, simple mathematical expressions are used. All new terms are defined fully.

WHY THE PROGRAMMED TEXT FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and by the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included at the end of each of these two-page segments. Most of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given at the top of the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming ensures that you will advance through the text as quickly as you are able to absorb what has been presented.

HOW YOU SHOULD STUDY THIS TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study, in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence presents or supports a thought which is important to your understanding of the technology.
2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.
3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most answers are short.
4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you do not know the answer, even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still have not come to you, turn the page and check the answer section.
5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the material. Knowing the correct answer to a question is less important than understanding why it is

correct. Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.

6. Carefully study the Summary Questions at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across questions you do not completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.
7. Complete the final test at the end of the book. This test reviews the complete text and will offer you a chance to find out just what you have learned. It also permits you to discover your weaknesses and initiate your own review of the volume.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study will be a pleasant and interesting experience.

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1

Introduction to Transistors

What You Will Learn

In this chapter you will learn of some of the applications of transistors. You will discover why they have all but replaced the vacuum tube as the major component in electronic equipment. You will learn that the principles that explain the operation of the transistor are the same principles that explain the operation of all basic electrical circuits—voltage, current, and impedance. You will see that the transistor is nothing more than a current-controlling device. This chapter closes with a summary of the material covered in this volume.

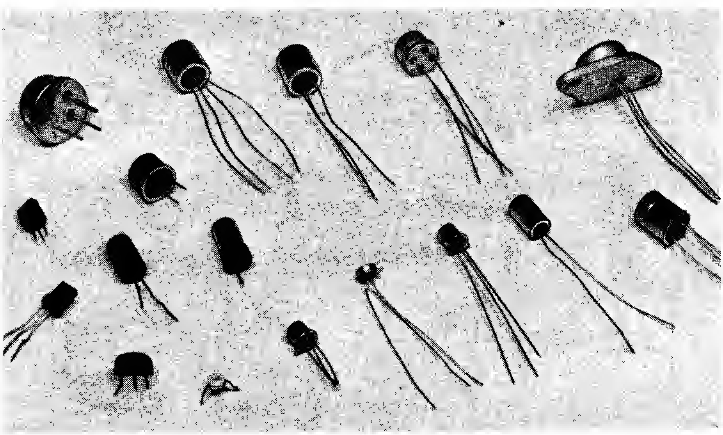


Fig. 1-1. Transistors vary in size and shape.

TRANSISTOR APPLICATIONS

Probably the greatest single advance in electronics since the invention of the vacuum tube by Dr. Lee de Forest in 1907 was the invention of the transistor. Oddly enough, the development of the transistor started one year before the invention of the vacuum tube. In the year 1906, a silicon crystal was used as a crystal detector, the cat whisker of the early crystal radio. However, through a quirk of fate, the transistor did not reach the electronic world until 1948.

Fig. 1-2 shows a few of the many applications that have become almost the exclusive property of the transistor. One of the major reasons for the success of the transistor is its small size. This has resulted in its extensive use in portable equipment, such as radios and television sets, as well as in medical equipment, such as the pacemaker—a device that has saved the lives of many heart patients. In the field of space exploration, where there is a premium on room in every package delivered, the transistor has led the field. Weather satellites give us a better picture of the world we live in and communication satellites make it possible for us to transmit television signals even around the world. Radar sets search the skies for planes, missiles, and weather information, while sonar devices map the ocean floor, search

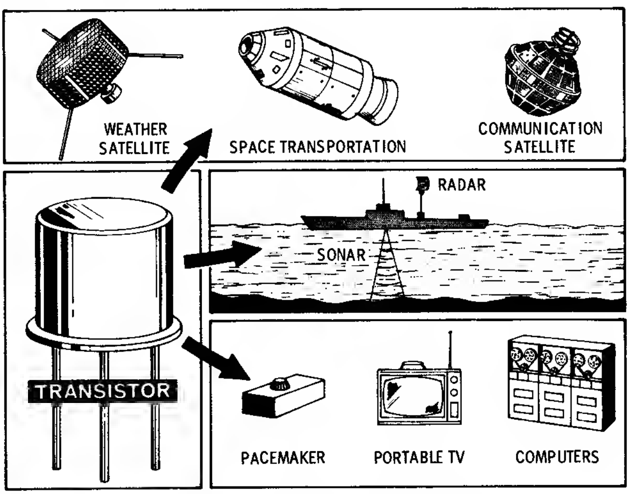


Fig. 1-2. Transistor applications.

for submarines, or locate schools of fish. All around us in office buildings all over the world, computers plug away at problems turning out in millionths of a second data that formerly took hours.

WHY ARE TRANSISTORS USED?

What is it about the transistor that has caused it to be used in the electronics industry almost to the exclusion of all other devices? Four of these reasons—size, power requirements, life, and cost—are discussed in the following paragraphs.

Size

Prior to the development of the transistor, the component used in most electronic applications was the vacuum tube. Compared to this component you can see in Fig. 1-3 how the transistor is one of the greatest space savers of all time.

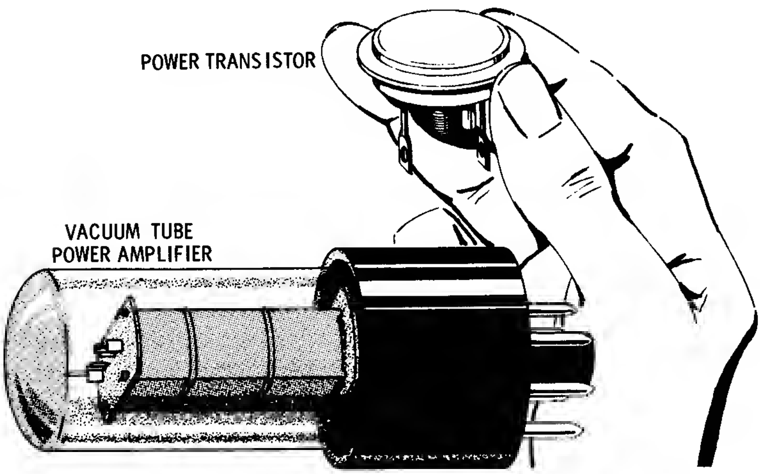


Fig. 1-3. Transistors are smaller than tubes.

Q1-1. Vacuum tubes are being replaced by ________.

Q1-2. Early radios used a principle of the ________.

Q1-3. One of the major reasons for the use of transistors in portable equipment and space exploration is their ________ ________.

Your Answers Should Be:

A1-1. Vacuum tubes are being replaced by **transistors.**

A1-2. Early radios used a principle of the **transistor.**

A1-3. One of the major reasons for the use of transistors in portable equipment and space exploration is their **small size.**

Power Requirements

Due to its size and construction (Fig. 1-4) the transistor requires very little power to operate. Where a vacuum tube

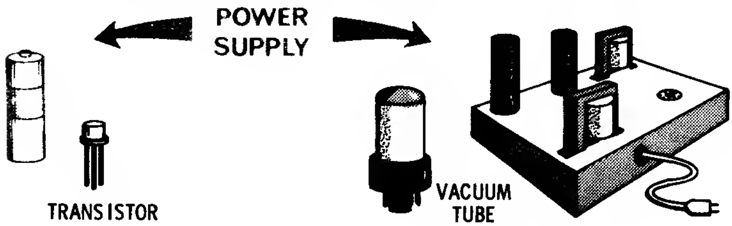


Fig. 1-4. Transistor power requirements are low.

may require a complicated power supply, a comparable transistor will only need a small dry cell battery.

Life

The construction of vacuum tubes has caused them to be plagued with breakdowns. Fig. 1-5 shows some of the causes for malfunctions in vacuum tubes—low emission, broken envelopes, gassy and microphonic tubes, and open filaments. As shown in the illustration, while several tubes have been replaced in the vacuum-tube equipment, the transistorized equipment has yet to undergo a repair. The mechanical and

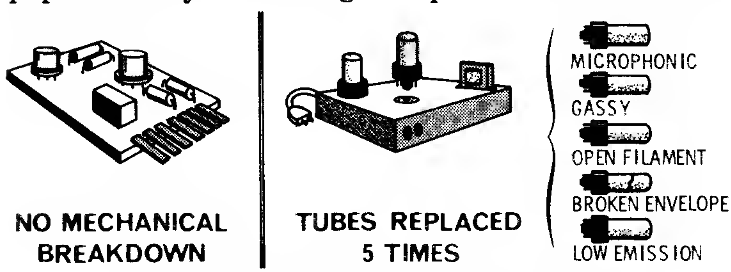


Fig. 1-5. Transistors last longer than tubes.

chemical construction of the transistor is so simple that its life under normal applications is almost unlimited.

Cost

When transistors were first developed, they were much the same price as the vacuum tubes they replaced. As soon as industry tooled up for the mass production of transistors, their price decreased rapidly, and today it is not unusual to find that for the cost of one vacuum tube you might pur-

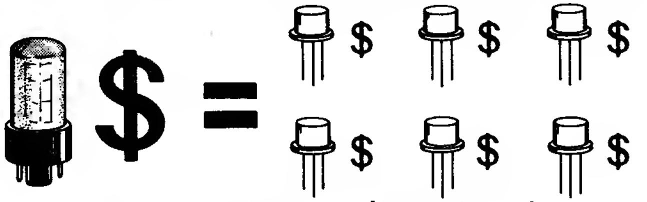


Fig. 1-6. Transistors are cheaper than tubes.

chase several transistors. By reducing the cost of transistors (as well as other electronic components), the maintenance of transistorized equipment has been simplified tremendously. Many of the components are so cheap that they are considered expendable ("throw-away items" in the jargon of the electronics industry) and can be thrown away when found faulty.

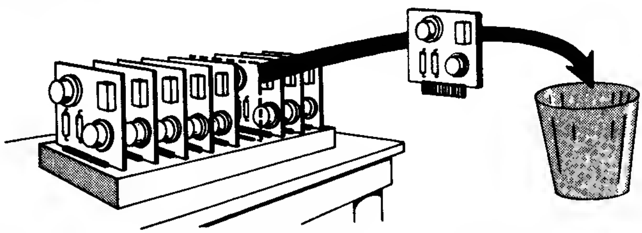


Fig. 1-7. Transistorized components are cheap enough to be expendable.

Q1-4. Transistors require much ________ power to operate than vacuum tubes.

Q1-5. The life of a ________ is much longer than that of a ________.

Q1-6. The fact that many electronic components are considered throw-away items today is due to the ________ ________ of transistors.

Your Answers Should Be:

A1-4. Transistors require much **less** power to operate than vacuum tubes.

A1-5. The life of a **transistor** is much longer than that of a **tube.**

A1-6. The fact that many electronic components are considered throw-away items today is due to the **low cost** of transistors.

TRANSISTOR PRINCIPLES

The same principles that explain the operation of the transistor are those that are the basis for all electronics. They are *voltage, current,* and *impedance.*

Voltage

Voltage is a potential force. It is a force similar to the motor which moves a car, or the pump which propels water through pipes. Sources of voltage are batteries and generators. Like any other force voltage can cause motion—hence its name of electromotive force or emf. This force causes the electrical motion called current.

Current

The motion caused by the motor is the movement of the car. The motion caused by the pump is the flow of water. The motion caused by voltage is current, which is the motion or flow of electrical particles called electrons.

Impedance

Impedance controls the rate of current as road conditions control the movement of cars, as shown in Fig. 1-8. Even though the cars in the illustration have the same motors, the number of cars passing down the dirt road in one hour will be less than the number passing down the highway. The dirt road offers a higher *resistance* to the flow of traffic than does the concrete highway, thus *impeding* the flow of traffic. Thus the cars must adjust their speed to the different road conditions even though they are all capable of the same

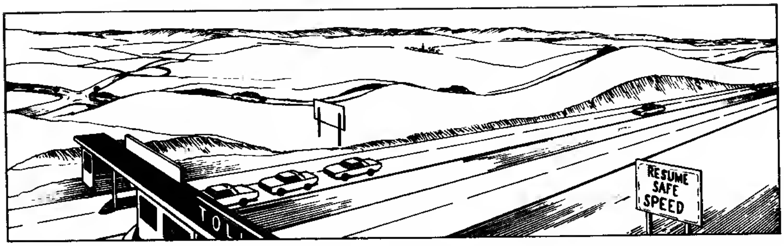


Fig. 1-8. A dirt road offers high resistance to traffic.

speed. Now look at the pumps in Fig. 1-9. Each of these pumps has the same capacity to pump water, but one pumps through a straight pipe and the other must pump through a curved pipe (of the same length). Note that the number of gallons per minute leaving one pipe will be less than that leaving the other.

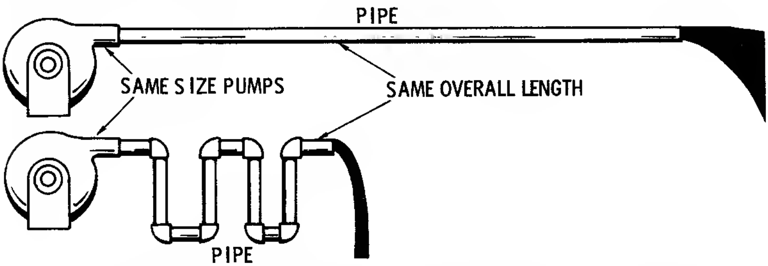
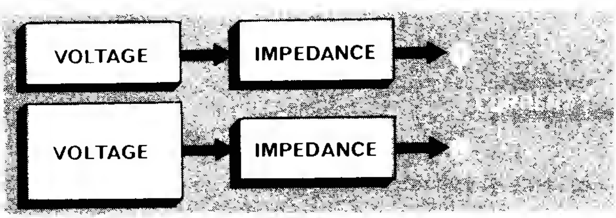


Fig. 1-9. Which pipe offers the least resistance to water flow?

Q1-7. In the preceding illustration the curved pipe offers a(n) ________ ________ to the flow of water than the straight pipe.

Q1-8. More water per minute will flow through the ________ pipe than through the ________ pipe.

Q1-9. In the illustration below, system (one, two) will have the most current.

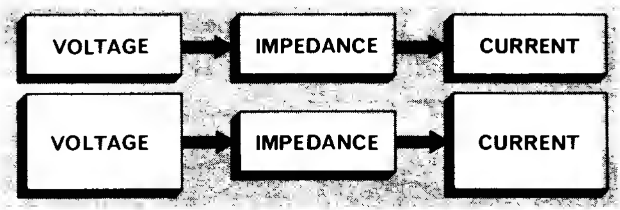


Your Answers Should Be:

A1-7. In the preceding illustration, the curved pipe offers a **higher resistance** to the flow of water than does the straight pipe.

A1-8. More water per minute will flow through the **straight** pipe than through the **curved** pipe.

A1-9. In the illustration below, system **two** will have the most current. Since the impedance to current is the same in both systems, then the system with the most voltage will have the highest current.



A TRANSISTOR IS A CURRENT-CONTROLLING DEVICE

Just as impedance controls current, the transistor can also control current. Fig. 1-10 shows that a small current at the input to a transistor can cause a large current at the output of the transistor. Although this is not exactly the

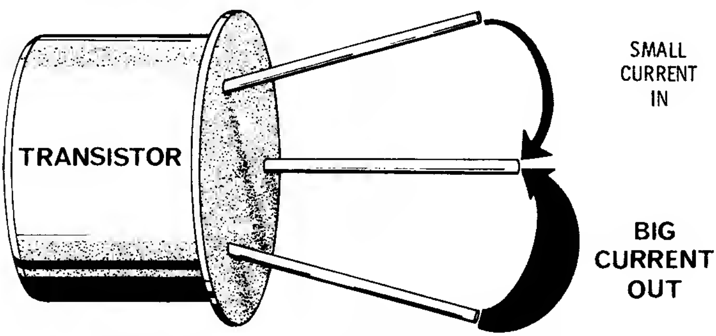


Fig. 1-10. A transistor uses current to control current.

case, it is sufficiently true for the purposes of this volume. Volume 2 will cover the transistor in detail. It is enough to know now that the transistor is an impedance device that changes its output impedance when the input current changes.

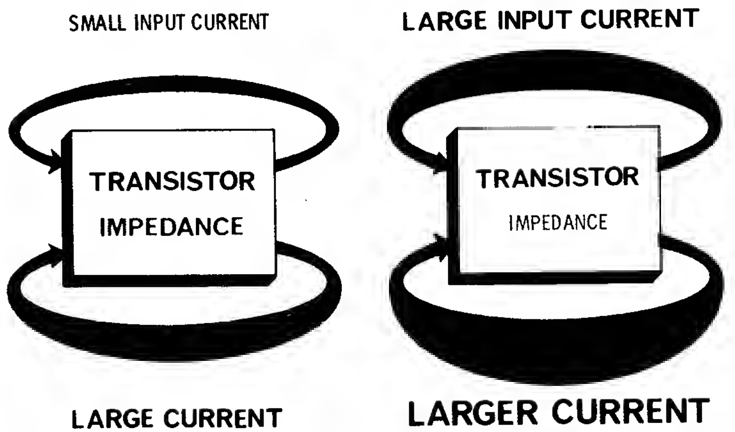


Fig. 1-11. Changing input current changes output impedance.

Fig. 1-11 shows the transistor capability that has made the device the important component that it is today. Notice how a small current in part A is applied to the transistor causing a certain large current through the output impedance of the transistor. In part B the input current has been increased, reducing the output impedance, and therefore increasing the output current.

Q1-10. The output ________ of a transistor can be varied by changing the input ________.

Q1-11. In order to decrease the output current of a transistor it is necessary to ________ the output impedance of the transistor.

Q1-12. In order to decrease the output impedance of the transistor it is necessary to ________ the input current of the transistor.

Q1-13. The transistor controls current by acting like a variable ________.

Your Answers Should Be:

A1-10. The output **current** of a transistor can be varied by changing the input **current.**

A1-11. In order to decrease the output current of a transistor it is necessary to **increase** the output impedance of the transistor.

A1-12. In order to decrease the output impedance of the transistor it is necessary to **increase** the input current of the transistor.

A1-13. The transistor controls current by acting like a variable **impedance.**

PREVIEW OF VOLUME 1

As you can see, if you wish to understand the operation of the transistor you must have a good basic knowledge of electrical and electronic principles. The rest of this volume is devoted to giving you this knowledge so that you can learn the transistor principles developed in Volume 2 of this series.

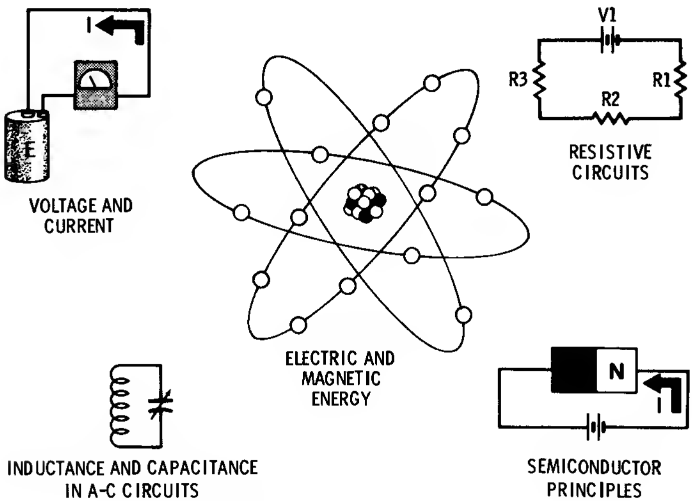


Fig. 1-12. Preview of Volume 1.

SUMMARY QUESTIONS

1. The transistor ranks as one the most significant developments in electronics since the vacuum tube.
   a. Transistors are used in portable equipment because of their ________ size and minute ________ requirements.
   b. The low cost of transistors is made even lower when you consider the ________ life of transistors.
2. The transistor controls current by serving as a variable impedance.
   a. Increasing the voltage in a system will ________ the current.
   b. Decreasing the impedance in a circuit will ________ the current.
3. A knowledge of the basic principles of electricity, voltage, current, and impedance is all that is required to understand the operation of the transistor.
   a. The transistor is a ________ controlling device.
   b. Changes in the output impedance of the transistor cause changes in the output ________.
   c. To increase the output impedance of the transistor you must ________ the input current to the transistor.
   d. To increase the output current of a transistor you must ________ the input current.

SUMMARY ANSWERS

1a. Transistors are used in portable equipment because of their **small** size and minute **power** requirements.

1b. The low cost of transistors is made even lower when you consider the **long** life of transistors.

2a. Increasing the voltage in a system will **increase** the current.

2b. Decreasing the impedance in a circuit will **increase** the current.

3a. The transistor is a **current** controlling device.

3b. Changes in the output impedance of the transistor cause changes in the output **current.**

3c. To increase the output impedance of the transistor you must **decrease** the input current to the transistor.

3d. To increase the output current of a transistor you must **increase** the input current.

2

Electric and Magnetic Energy

What You Will Learn

In this chapter you will learn what matter is and its relationship to molecules, elements, and atoms. The structure of the atom and the functions of the electron, proton, and neutron are discussed. You will learn how atoms may be charged either positively or negatively and how free electrons may be caused to flow under the effect of a potential difference. You will learn about magnetism, static electricity, and how a magnet may be made from an iron bar and electrical energy.

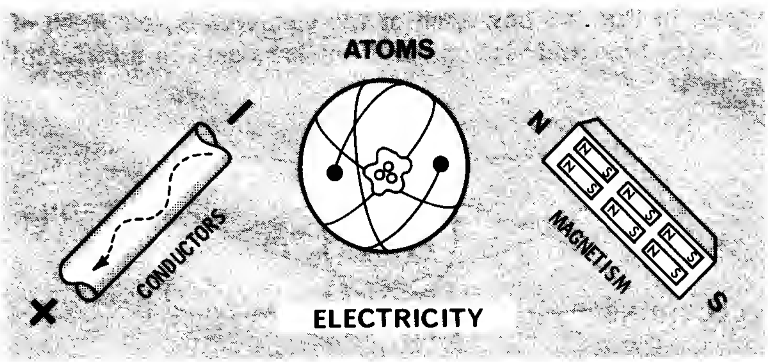


Fig. 2-1. Electricity.

MATTER

Definition of Matter

To understand transistor operation, one must first understand the structure of matter. Matter is anything that has weight. Food, water, clothing, and gold are matter. Air is matter, too. Radio waves, heat, and light are not matter; they are forms of energy.

Elements

The Element Defined—Long ago, scientists believed that all matter was composed of four basic ingredients: fire, water, earth, and air. Since they were considered the *elemental* forms of matter they were called elements. Centuries later this theory was proved wrong. Scientists were able to break matter into many pure substances. These substances could not be broken down any further and so they were called *elements*. They are identified by such properties as color, density, melting temperature, odor, and others. Today more than 100 elements have been discovered.

Elements Composed of Atoms—Many of the ancient scientists believed that these elements were composed of tiny particles called *atoms* (Fig. 2-2). It was later established that this was so—that all matter is composed of atoms. Each of these atoms consists of a *nucleus* that contains two types of particles: a *neutron* and a *proton*. Orbiting this nucleus is a third particle called an *electron*. The ancients also claimed that each of the elements was composed of the same atoms, only in different proportions and arrangements. Notice in Fig. 2-3 how each of the elements is composed of the same type and size of atom but arranged in a different fashion.

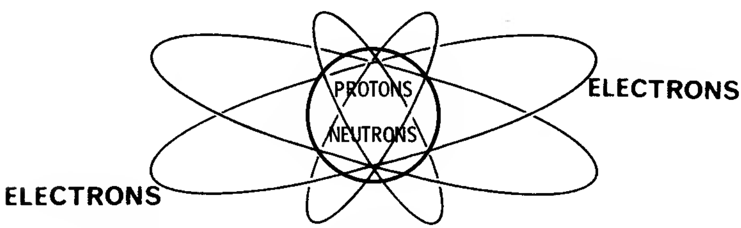


Fig. 2-2. The atom—building block of the universe.

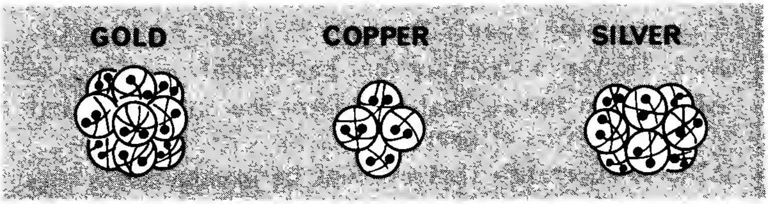


Fig. 2-3. An ancient view—elements composed of different combinations of the same atom.

Eighteenth century scientists rejected this and suggested that different kinds of atoms existed: that is, iron atoms, sulphur atoms, arsenic atoms, gold atoms, etc. Each kind of atom was supposed to have had its own size, shape, and weight. And so it was later proved that only like atoms combined to form elements (Fig. 2-4).

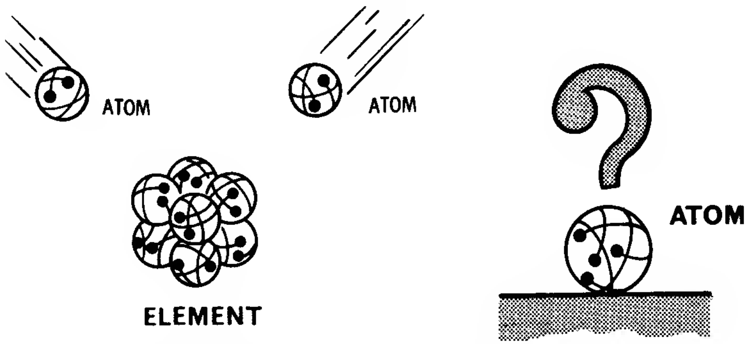


Fig. 2-4. Like atoms combine to form elements.

Q2-1. Matter is anything that has ________.

Q2-2. Radio waves, heat, and light are not ________ but are forms of ________.

Q2-3. A substance that cannot be broken down any further by chemical means is called an ________.

Q2-4. Atoms combine to form ________.

Q2-5. The particles found in the nucleus of an atom are the ________ and the ________.

Q2-6. The particle orbiting about the nucleus is the ________.

Your Answers Should Be:

A2-1. Matter is anything that has **weight.**

A2-2. Radio waves, heat, and light are not **matter** but are forms of **energy.**

A2-3. A substance that can not be broken down any further by chemical means is called an **element.**

A2-4. Atoms combine to form **elements.**

A2-5. The particles found in the nucleus of an atom are the **neutron** and the **proton.**

A2-6. The particle orbiting about the nucleus is the **electron.**

Molecules

A molecule is the smallest particle of a chemical substance capable of an independent existence. The atoms of most elements cannot exist by themselves, but they combine to form molecules (Fig. 2-5). In certain rare instances it is possible

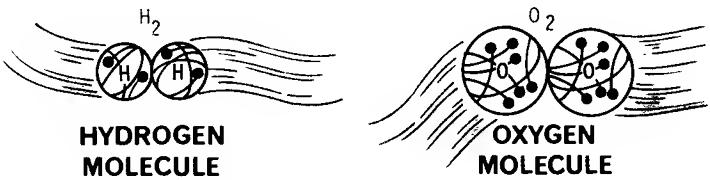


Fig. 2-5. Atoms combine to form molecules.

for an atom to be a molecule—such is the case with helium. Helium exists in its natural state as an atom and can be classified as a molecule. When elements combine they form

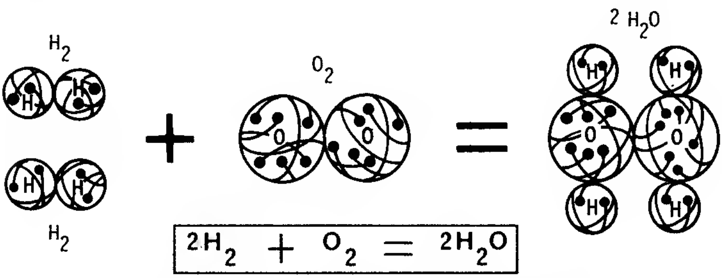


Fig. 2-6. Molecules combine to form compounds.

compounds. Fig. 2-6 shows how hydrogen and oxygen combine to form water, a compound. Four atoms of hydrogen have combined to form two molecules of hydrogen, and two atoms of oxygen have combined to form one molecule of oxygen. When the compound is formed it is the atoms of the elements that combine to form two molecules of water. The equation is:

$$2H_2 + O_2 = 2H_2O$$

STRUCTURE OF THE ATOM

Early Theories

In 1897 an Englishman discovered that a tiny unit of negative electricity was a part of every atom. Fig. 2-7 shows some of the theories of the structure of the atom that evolved from this discovery. In 1898 it was thought that

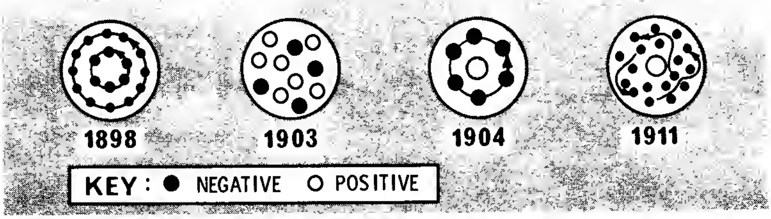


Fig. 2-7. The changing atomic theory.

an atom consisted of a large number of negatively charged particles that were contained in a ball-shaped positive field. In 1903 a theory showed pairs of positive and negative particles floating around in space. By 1904 it was thought that there was a circle of negatively charged particles surrounding a heavy positive center. Finally, in 1911 it was concluded that there was a positive charge concentrated at the center of the atom with electrons (negatively charged particles) swarming around this nucleus.

Q2-7. The smallest particle of a substance capable of independent existence is the ________.

Q2-8. Atoms cannot exist by themselves, but they combine to form ________.

Q2-9. When two or more elements combine they form a ________.

Your Answers Should Be:

A2-7. The smallest particle of a substance capable of independent existence is the **molecule.**

A2-8. Atoms cannot exist by themselves, but they combine to form **molecules.**

A2-9. When two or more elements combine they form a **compound.**

The Bohr Atom

In 1913, Niels Bohr came up with the theory of the structure of an atom that revolutionized atomic physics. Fig. 2-8 shows his model of the hydrogen atom. The electron rotates

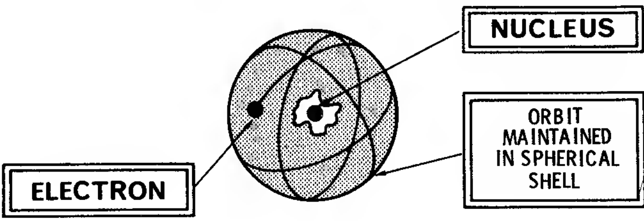


Fig. 2-8. The Bohr atom.

about the nucleus at a specific distance from the nucleus. The distance is set by the force of attraction of the nucleus. The electron is continuously acted upon by other electrical particles in nearby atoms. It changes its orbit constantly—always maintaining the same distance from the nucleus. Because the electron travels so fast—one hundred *million billion* orbits each second—the shell seems to be solid. This shell is called an energy level.

The Bohr Model of Heavier Elements

All atoms were assigned weights. The weight assignment was based on how much they weigh in relationship to an atom of oxygen. Thus, since hydrogen, the lightest atom, weighs 1/16th of oxygen its weight is 1. These weights are called atomic weights (approximate weights used in this book). Atoms are also assigned numbers that correspond to the number of electrons they contain. All atoms are electrically neutral. That is, they have the same number of elec-

trons (negative charges) as protons (positive charges). Thus the atomic number not only refers to the number of electrons, but also to the number of protons.

Fig. 2-9 shows the arrangement of the energy shells and electrons in the elements having atomic numbers of 2, 3, and 11. Helium, whose atomic number is 2, has two electrons orbiting in one shell. Lithium, atomic number 3, has two electrons orbiting in its first energy level (innermost shell), and one electron orbiting in its outermost energy level. Sodium, with an atomic number of 11, has two electrons in its first energy level, eight in its second energy level, and one in its third energy level. The greatest number of electrons that can be contained in one shell is 32.

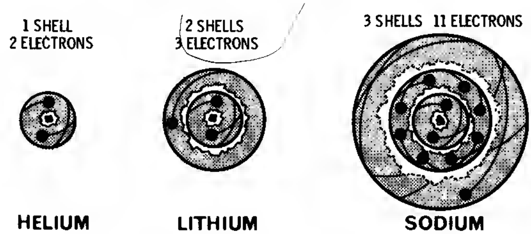


Fig. 2-9. Energy shells and electrons.

The atomic weight and atomic number of an element are not the same (except for hydrogen whose atomic weight and atomic number are both equal to 1). The atomic weight is made up of the number of protons (a figure equivalent to the number of electrons and also to the atomic number) plus the number of neutrons (the other particle contained in the nucleus). Note that the weight of these particles is almost equal and that they are more than 1840 times as heavy as an electron (which will be considered weightless for this discussion).

Q2-10. The electrons in the Bohr atom are arranged in shells or ________ ________.

Q2-11. Atomic weights are assigned by comparing the weight of the atom with the weight of an atom of ________.

Q2-12. All normal atoms are electrically ________.

Q2-13. The atomic number corresponds to the number of ________ or ________.

Your Answers Should Be:

A2-10. The electrons in the Bohr atom are arranged in shells or **energy levels.**

A2-11. Atomic weights are assigned by comparing the weight of the atom with the weight of an atom of **oxygen.**

A2-12. All normal atoms are electrically **neutral.**

A2-13. The atomic number corresponds to the number of **electrons** or **protons.**

ELECTROSTATICS

Static Electricity

Most of you are familiar with the term static electricity. You have probably experienced a small electrical shock that can result when you walk on a thick rug and then touch a metal object. Or maybe you have seen and heard the crackle of electricity when removing a woolen sweater in a darkened room. In Fig. 2-10 are shown two ways of generating static

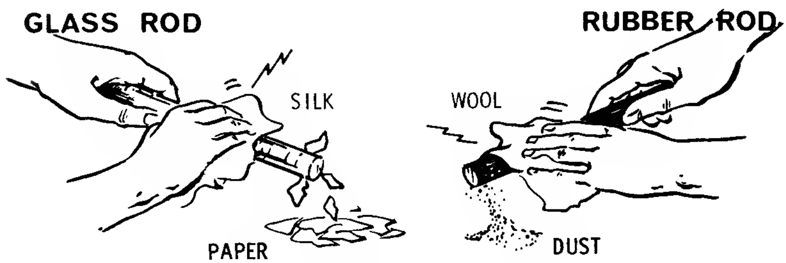


Fig. 2-10. Static electricity.

electricity. In one instance a glass rod is rubbed vigorously with a silk cloth. Sparks are observed in the dark and finally small pieces of paper are attracted to the glass rod. In another example a rubber rod is rubbed with a woolen cloth. Again the sparks result, and the rod is able to attract dust particles. Why does the rod take on seemingly magnetic properties?

Free Electrons

Compared to protons and neutrons, electrons are extremely mobile. They move in their orbits at tremendous speeds. In some atoms the outermost energy level is only partially occupied by electrons. For example, an atom of chlorine has seven electrons in its outer shell. The shell can hold a maximum of eight electrons. Since it lacks one electron from making its outer shell complete it tends to attract electrons to this space or hole in its shell. Sodium on the other hand has one electron in its outer shell which it would like to give up. This electron in the sodium atom is almost *free* to move about at will if the right conditions exist. Glass, like sodium, has electrons that are relatively free. Silk on the other hand is like chlorine in that it would like to receive electrons. The friction of rubbing the silk on the glass gives the free electrons on the glass enough energy to jump over the silk (Fig. 2-11). Since electrons have been removed from the glass it now has more protons than electrons and must be positively charged. The silk, having gained electrons, must be negatively charged.

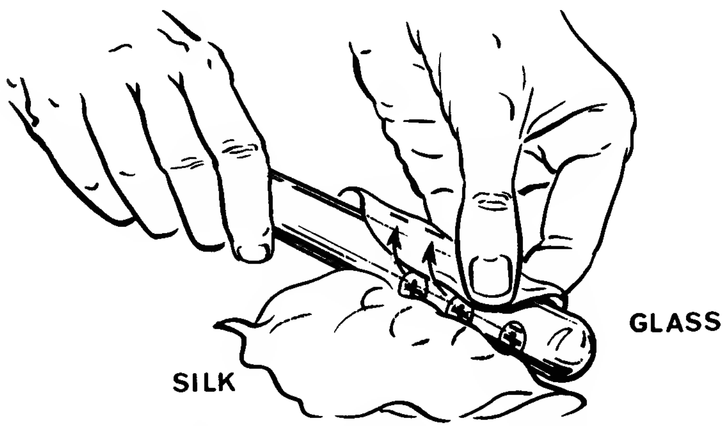


Fig. 2-11. Glass gives up electrons to silk.

Q2-14. The particle with the most mobility in an atom is the ________.

Q2-15. When a material loses electrons it is ________ charged.

Your Answers Should Be:

A2-14. The particle with the most mobility in an atom is the **electron.**

A2-15. When a material loses electrons it is **positively** charged.

Attraction and Repulsion of Charges

How does the glass pick up materials? First let us understand how charges react to each other. If two electrons are brought close together they will repel each other. If a proton is brought close to an electron it will attract the electron. Or, as you can see in Fig. 2-12, like charges repel and unlike charges attract. Now we can see how the glass attracts a

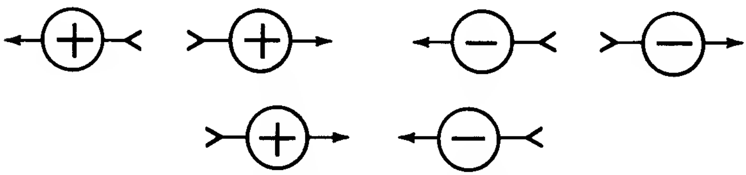


Fig. 2-12. Like charges repel—unlike charges attract.

neutral object like a small piece of paper (Fig. 2-13). The glass, which has a positive charge due to the loss of electrons to the silk, is allowed to touch the paper. Although the paper is neutral, it still has some free electrons. These electrons are attracted to the glass, and since they do not have enough energy to cross over to the glass, the paper is picked up. The case of the rubber rod is slightly different

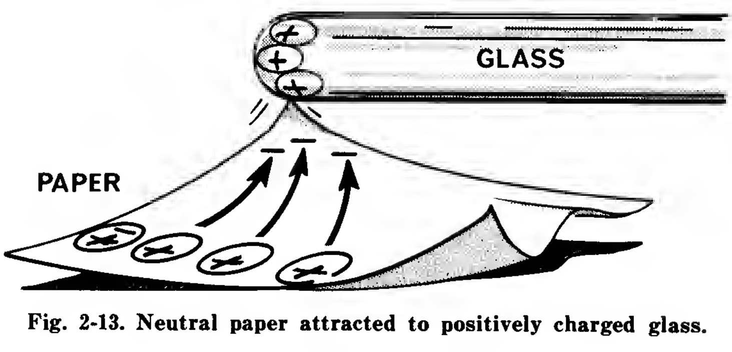


Fig. 2-13. Neutral paper attracted to positively charged glass.

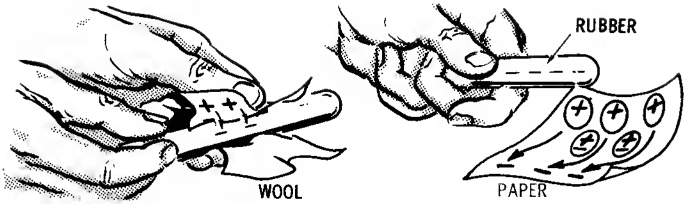


Fig. 2-14. Negatively charged rubber rod attracts neutral paper.

although the same principles are used. Fig. 2-14 shows that wool tends to give up electrons, while rubber tends to accept electrons. When the rubber rod is touched to the paper it tends to repel free electrons. They migrate to the other end of the paper leaving the end touching the rod positively charged. The paper is then picked up by the negatively charged rod.

Formation of Ions

Now let us return to sodium and chlorine. Fig. 2-15 shows the pertinent facts about the elements sodium (Na) and chlorine (Cl). When they are combined to form salt, they

ELEMENT	SYMBOL	ATOMIC WT	ATOMIC NO	PROTONS - ELECTRONS	NEUTRONS
SODIUM	Na	23	11	11	12
CHLORINE	Cl	35	17	17	18

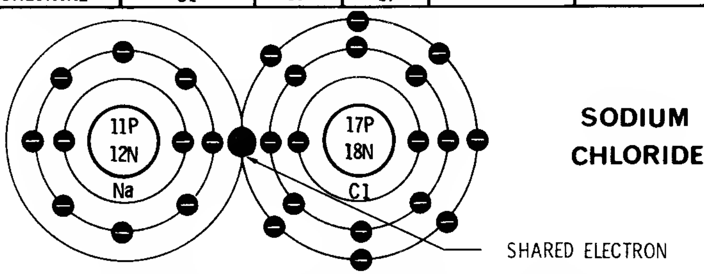


Fig. 2-15. Sodium shares an electron with chlorine.

share an electron as shown in the illustration. This satisfies both sodium's desire to give up the free electron in its outer shell and chlorine's desire to complete its outer shell of only seven electrons.

Q2-16. Like charges ______ and unlike charges ______.

Q2-17. The shared electron in the above illustration belongs to _______.

Your Answers Should Be:

A2-16. Like charges **repel** and unlike charges **attract.**

A2-17. The shared electron in the illustrations belongs to **sodium.**

If sodium chloride in its molten state (heated until it is a thick liquid) is placed in a container and then has electricity passed through it, an interesting phenomenon occurs (Fig. 2-16). The molecules of sodium chloride separate. The chlorine takes the electron that was being shared with it,

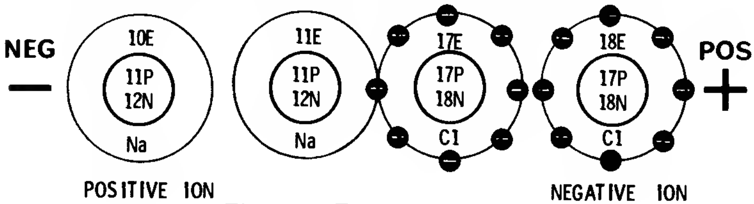


Fig. 2-16. Formation of ions.

thus completing the outer shell, but adding an extra electron. It is therefore negatively charged, and it is called a *negative ion.* The sodium has given up one electron to the chlorine and is therefore positively charged. It is called a *positive* ion. The negative ions will migrate to the positive terminal of the source of electricity. The positive ions (sodium) will migrate to the negative terminals of the source of electricity. When the negative ion arrives at the positive terminal it will give up the extra electron in its outer shell. This electron will pass around to the negative terminal where it will be reunited with the positive sodium ion. These two atoms (the chlorine at the positive terminal and the sodium at the negative terminal, may now join together and share the electron as before. By constantly repeating this process, electricity is caused to flow through the molten salt. We may say that molten salt *conducts* electricity.

Conductors, Semiconductors, Insulators

For the purposes of electronics we must consider materials as either good conductors of electricity, poor conductors of electricity, or not conductors of electricity at all. Con-

sider a good conductor of electricity such as copper; most electrical wire is made from copper.

A conductor is a substance through which electrons will move readily. The conditions for such movement are simple. We have seen that an electron placed in the vicinity of a proton will move in that direction. Thus the electron has the *potential* for movement. However, we can improve that potential by placing a lot of protons nearby and also by one

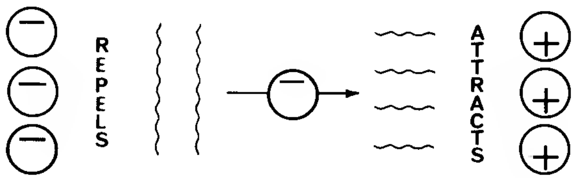


Fig. 2-17. Electron moves due to difference of potential.

other method; that is, by placing negative charges (electrons or ions) on the other side of the electron (Fig. 2-17). The bigger the difference is between the positive and negative charges the faster the electron moves. This difference in the amount of charges is referred to as a *difference in potential.* When such a difference in potential is applied to a copper wire, there is a current in the wire, as shown in Fig. 2-18.

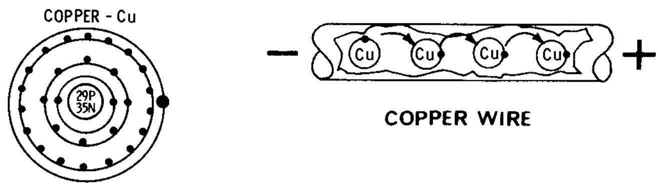


Fig. 2-18. Current in a copper wire.

Copper atoms have one electron in their outer shells. This electron, a free electron, migrates toward the positive potential by going from outer shell to outer shell.

Q2-18. When an atom gains an electron to complete its outer shell it is a ________ ion.

Q2-19. The difference between the number of electrons in one place and the number of electrons in another place is called ________ difference.

Your Answers Should Be:

A2-18. When an atom gains an electron to complete its outer shell it is a **negative** ion.

A2-19. The difference between the number of electrons in one place and the number of electrons in another place is called **potential** difference.

A conductor can be thought of as a material that has many free electrons (Fig. 2-19). It is usually a metal, and has one or maybe two electrons in its outer shell. Insulators are those materials that have practically no free electrons and offer a great deal of resistance to the flow of electricity. Semiconductors on the other hand have a limited ability to pass electrons. There are ways to treat semiconductors so that they will or will not act like conductors under certain conditions. It is this latter capability that makes them useful in the manufacture of transistors. Note that if the potential difference across an insulator is made large enough, there will be a current; however, the material will be destroyed.

ELECTROMAGNETISM

Magnetism

You are all familiar with the common magnet, the one that will pick up paper clips or serve as a compass needle (Fig. 2-20). What is it about certain materials that gives them the property called magnetism? Ancient man had been aware that there were certain materials in nature that would attract other materials; for example, lodestone attracting iron. Modern man has made inroads into the explanation of this phenomenon.

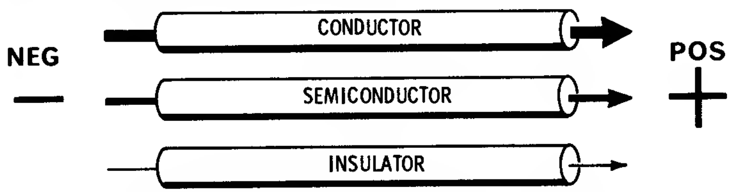


Fig. 2-19. The nature of electrical conductors.

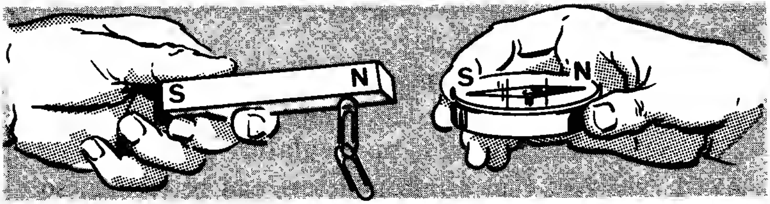


Fig. 2-20. Magnetism.

Electrons in Motion

The motion of electrons causes magnetic fields to be set up. For example, the orbital electron shown in Fig. 2-21 generates a magnetic field as shown, with a north pole in an upward direction and a south pole in the downward direction. In the same illustration you see how the spinning

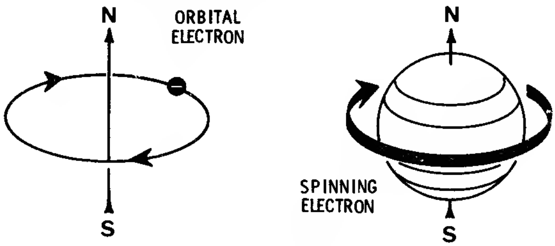


Fig. 2-21. Electron movement—source of magnetism.

of an electron causes a magnetic field. Those materials that exhibit magnetic properties owe 90 percent of this property to the spin of the electrons about their own axis and only about 10 percent to the orbiting of the electrons. All materials contain electrons that move in these fashions but there is something peculiar about the electron motion in magnetic materials.

Q2-20. A conductor has many ________ electrons.

Q2-21. The material that offers much resistance to the flow of electrons is an ________.

Q2-22. The fact that semiconductors can be treated so that they act like either conductors or insulators is what makes them useful as ________.

Q2-23. Electrons in motion cause ________ fields.

Q2-24. The major reason for magnetic materials is the (spin, orbiting) of electrons.

Your Answers Should Be:

A2-20. A conductor has many free electrons.

A2-21. The material that offers much resistance to the flow of electrons is an **insulator.**

A2-22. The fact that semiconductors can be treated so that they act like either conductors or insulators is what makes them useful as **transistors.**

A2-23. Electrons in motion cause **magnetic** fields.

A2-24. The major reason for the magnetic property of materials is the **spin** of electrons.

In most atoms electrons move in pairs. These pairs have spins in opposite directions, as shown in Fig. 2-22. Although each of these electrons generates a magnetic field, the results are nullified since the fields are of equal magnitudes but in opposite directions (pairs A and B in Fig. 2-22). Pair C on the other hand shows two electrons rotating in the same direction. The generated magnetic fields tend to reinforce rather than cancel each other. Electrons that are paired in this fashion are found in magnetic materials. A group of electrons like those shown in pair C join to form a magnetic *domain.* In most magnetic materials these magnetic domains are not aligned; that is, domains from different atoms face in different directions, as shown in Fig. 2-23. As a result they do not reinforce each other and the material is not yet magnetized. By methods which we will examine later, these domains may be aligned, with the result being the magnetized material. A few substances have domains already aligned and are considered permanent natural magnets.

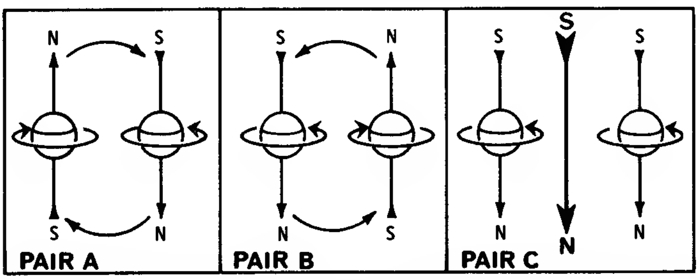


Fig. 2-22. Electrons spinning in same direction reinforce magnetic field.

Magnetic Fields

In a magnetized material such as the bar magnet shown in Fig. 2-24, the magnetic fields of all the domains line up so that the magnetic lines of force leave the north pole and

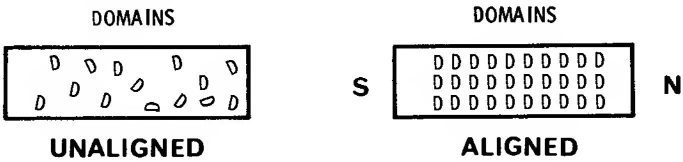


Fig. 2-23. Formation of a magnet.

enter the south pole. Note that the lines of force do not intersect each other but strain to keep their distance. The illustration shows very few of the millions of lines of force

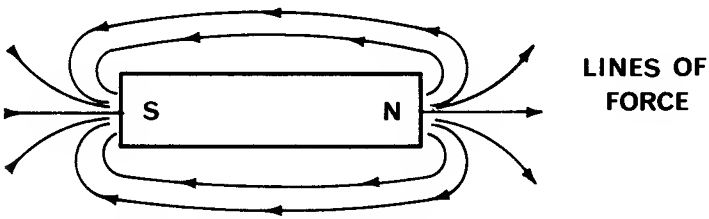


Fig. 2-24. Magnetic field around a bar magnet.

that would appear around a magnet. Just like electrical charges, magnetic poles exhibit the same behavior. That is, like poles repel and unlike poles attract (Fig. 2-25).

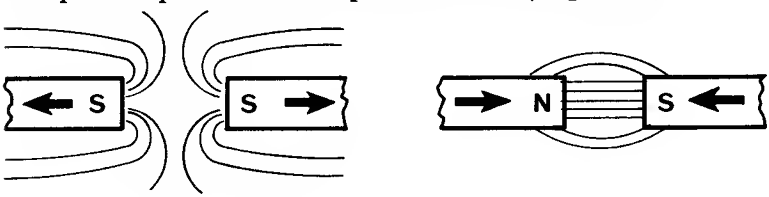


Fig. 2-25. Like poles repel—unlike poles attract.

Q2-25. The magnetic fields formed by electrons that spin in the same direction are called ________.

Q2-26. In order to form a magnetic material the domains must be ________.

Your Answers Should Be:

A2-25. The magnetic fields formed by electrons that spin in the same direction are called **domains.**

A2-26. In order to form a magnetic material the domains must be **aligned.**

Potential Difference Caused by Magnetism

Fig. 2-26 shows how electron flow through a conductor generates a magnetic field around the conductor. Note that this field will exist for the entire length of the conductor. Note also that it took a potential difference from one side

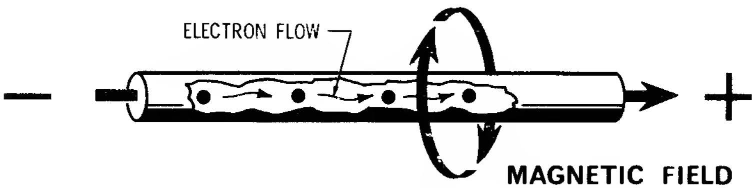


Fig. 2-26. Electron flow causes magnetic field.

of the wire to the other to cause the electrons to flow through it. Now examine what happens when we move a conductor through a magnetic field. In Fig. 2-27 we see a conductor moving through the magnetic field formed by the north and

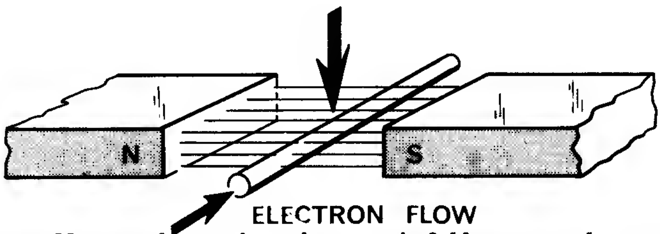


Fig. 2-27. Move conductor through magnetic field to cause electron flow.

south poles of two magnets. As it cuts through the magnetic lines of force, an electron flow is noticed in the conductor. We know that in order for electrons to flow there must be a difference of potential. Therefore, it must follow that a potential difference was generated across the wire when it was passed through the magnetic field.

SUMMARY QUESTIONS

1. The atom is the basic building block of all matter.
   a. Protons and neutrons are found in the ________ of the atom.
   b. The particle of an atom that moves in an orbit is the ________.
2. The structure of the atom was finally discovered by Niels Bohr.
   a. Atoms are electrically neutral because they have the same number of ________ and ________.
   b. Complete this table.

ELEMENT	ATOMIC NUMBER	ATOMIC WEIGHT	PROTONS	NEUTRONS	ELECTRONS
HYDROGEN	1	1			
HELIUM		4	2		
LITHIUM	3			4	
SODIUM		23			11
COPPER			29	35	

3. The nature of static electricity, when explained, gives you the basics for the understanding of electricity.
   a. Rubbing a glass rod with silk causes ________ electrons to collect on the silk.
   b. Like charges ________ and unlike charges ________.
   c. A material through which electrons pass readily is called a ________.
   d. If it is desirable to prevent electrons from flowing from one conductor to another adjacent conductor they should be separated by an ________.
   e. In order to cause electron flow through a conductor it is necessary to provide a ________ difference.
4. The phenomenon of magnetism is caused by electron motion.
   a. Magnets are formed by the alignment of ________.
   b. Show the polarity of the difference of potential generated in Fig. 2-27.

SUMMARY ANSWERS

1a. Protons and neutrons are found in the **nucleus** of the atom.

1b. The particle of an atom that moves in an orbit is the **electron.**

2a. Atoms are electrically neutral because they have the same number of **electrons** and **protons.**

2b.

ELEMENT	ATOMIC NUMBER	ATOMIC WEIGHT	PROTONS	NEUTRONS	ELECTRONS
HYDROGEN	1	1	1	0	1
HELIUM	2	4	2	2	2
LITHIUM	3	7	3	4	3
SODIUM	11	23	11	12	11
COPPER	29	64	29	35	29

3a. Rubbing a glass rod with silk causes **free electrons** to collect on the silk.

3b. Like charges **repel** and unlike charges **attract.**

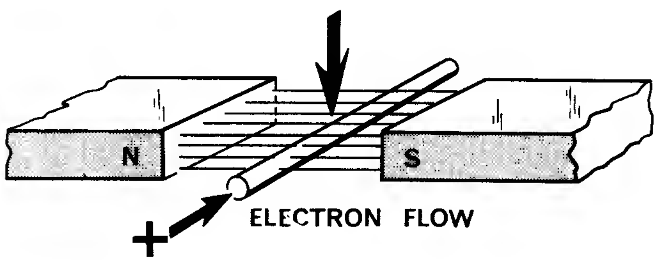
3c. A material through which electrons pass readily is called a **conductor.**

3d. If it is desirable to prevent electrons from flowing from one conductor to another adjacent conductor they should be separated by an **insulator.**

3e. In order to cause electron flow through a conductor it is necessary to provide a **potential** difference.

4a. Magnets are formed by the alignment of **domains.**

4b.



3

Voltage and Current

What You Will Learn

In this chapter you will learn about work and energy and how they are related to electronics. You will gain an understanding of the basic electrical units of voltage and current. Methods of generating electromotive force (emf) will be explained, with particular emphasis being placed on the dry cell and the alternating-current generator. A great deal of this chapter will be devoted to explaining the nature of alternating current. Such topics as the development of a voltage sine wave, voltage and current measurement, and the nature of time as related to the a-c signal will lead the student to a thorough knowledge of alternating current. The chapter concludes with a discussion of the relationship of current and voltage in a circuit, and the nature of a-c power.

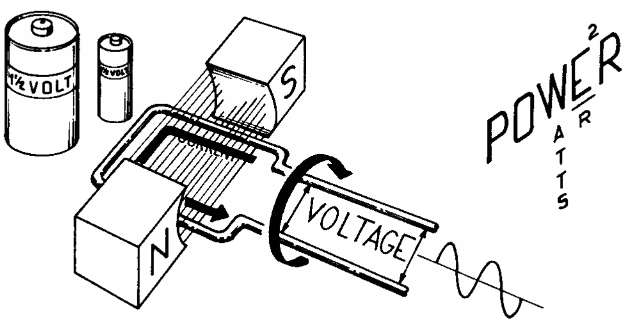


Fig. 3-1. Voltage sources.

WORK AND ENERGY

What Is Work?

Strange question? Not really! Many a man has returned from a hard day at the golf course and has had a difficult time convincing his wife that he has been "working." Once and for all we will settle this question. Whenever a *weight* is moved a *distance* by exerting a *force, work* is done. Under this definition not only does golf qualify as work, but so do bowling and many other entertaining activities. Examine Fig. 3-2. A man is shown in three stages of his approach

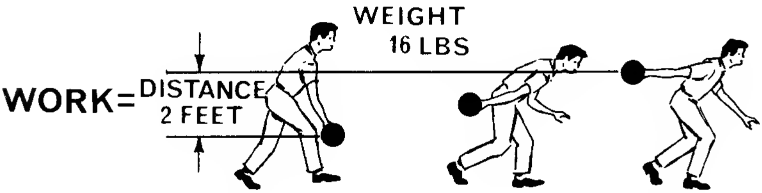


Fig. 3-2. When weight is moved through a distance, work is done.

to the bowling lane. As he progresses toward the foul line he raises the bowling ball (which weighs about 16 pounds) a distance of 2 feet. He does this against the force of gravity which opposes this motion. He has done some work. How much? Work is measured by determining the amount of force necessary to move the weight, and then multiplying it by the distance the weight was moved. Thus, as has been illustrated, the man moves a weight of 16 pounds a distance of 2 feet and the resultant work done is 32 foot-pounds (Fig. 3-3). If we take into account the force of gravity then the work is called the foot-pound*al*. The unit of force in this case would be the pound*al*.

$$\text{WORK} \left\{ \begin{array}{l} = \text{FORCE X DISTANCE} \\ = \text{16 LBS X 2 FT} \\ = \text{32 FOOT - POUNDS} \end{array} \right.$$

Fig. 3-3. One unit of work is the foot-pound.

Some Other Units of Work

When we deal in other systems of measurement we must consider different units of work. For example, Fig. 3-4 shows the work units associated with the gram-centimeter and kilogram-meter systems of measurement. Note here that when a gram of weight is moved a centimeter the result

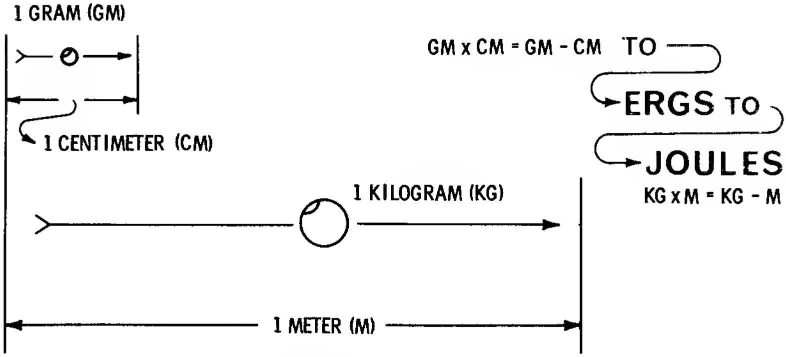


Fig. 3-4. Other units of work or energy.

is a gram-centimeter (gm-cm) of work. When we consider a gram of force used against gravity then the gram of force becomes a dyne (the unit of force in this system). The work done is then in dyne-centimeters (just like the foot-poundal). However, the dyne-centimeter is often referred to as an *erg*. Since the erg is such a small quantity of energy it is more usual to consider a work unit called the *joule* (= 10,000,000 ergs). In the same fashion, kilograms of force can be converted into *newtons* by considering the force of gravity, and the resultant unit of work, the newton-meter, can be converted into joules.

Q3-1. The factors that determine the amount of work done are ________ and ________.

Q3-2. The most common unit of work in the gram-centimeter system is the ________.

Your Answers Should Be:

A3-1. The factors that determine the amount of work done are **force** and **distance.** If you said weight and distance you are wrong. The amount of force necessary to move the weight is the determining factor. Consider moving two identical weights up a hill. If one of these is on wheels and the other is not, it is obvious that you will use more force to move the one without the wheels. This is due to the force of friction which opposes your force.

A3-2. The most common unit of work in the gram-centimeter system is the **joule.**

DIFFERENCE OF POTENTIAL

What Force Moves Electrons?

In the last chapter we found that electrons tend to move from areas where there is an excess of electrons to areas where there is a sparsity of electrons. By making the difference between two such areas great, the *potential* for the electron to move from one area to the other is increased. We call the difference in electrical charge between two points the *difference in potential,* and it is measured in a unit called the volt. Refer to Fig. 3-5. Here we consider a difference in potential between points A and B. Let us consider moving some electrons from A to B. How many should we consider?

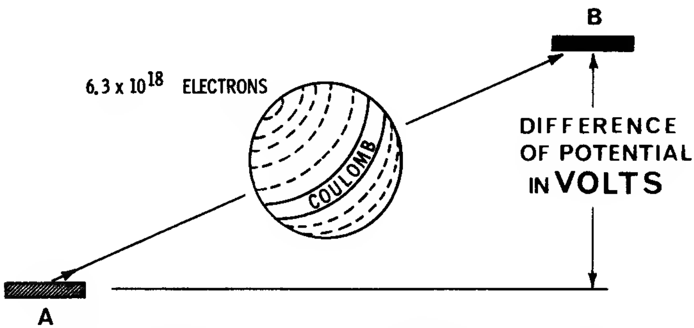


Fig. 3-5. Electrons moved by difference of potential.

Just as the erg is too small to consider as a unit of work, so is the electron too small a unit to consider moving. To consider practical motion we must take 6.3×10^{18} electrons (6,300,000,000,000,000,000), a number of electrons called a *coulomb*. For convenience we consider them bound together in the shape of a sphere. If we measure the amount of energy expended in moving them from point A to point B, and it turns out to be *1 joule*, then the difference of potential between point A and B is *1 volt*. Or another way of saying

$$\frac{\text{JOULE}}{\text{COULOMB}} = \text{VOLT}$$

Fig. 3-6. A volt is a joule per coulomb.

this is that a *volt* is a force that will cause a *joule* of energy to be expended in moving a *coulomb* of electrical charge. Or more simply—a *volt* is a *joule* per *coulomb* (Fig. 3-6).

How is Electron Flow Measured?

The movement of electrons from one place to another is called current. Just as water flow is measured in units like feet per minute, so can electrons be measured in terms of the number of electrons to pass a point in a unit of time. When a coulomb of electrons passes a point in one second, we call that a current of *1 ampere* (Fig. 3-7).

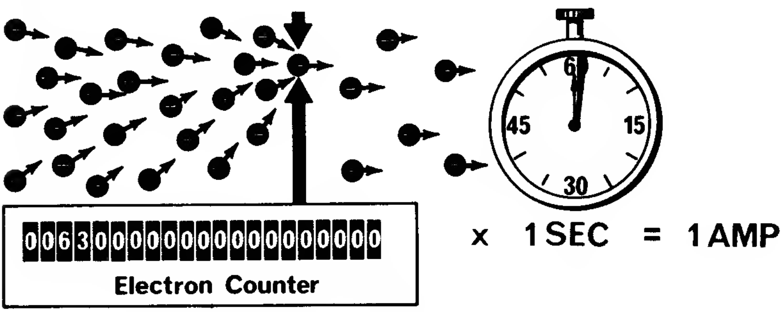


Fig. 3-7. A coulomb per second is an ampere.

Q3-3. A volt is a ________ per ________.

Q3-4. An ampere is a ________ per ________.

Your Answers Should Be:

A3-3. A volt is a **joule** per **coulomb.**

A3-4. An ampere is a **coulomb** per **second.**

GENERATING VOLTAGE

Friction

In Chapter 2 you were shown how rubbing a glass rod with silk created a small difference of potential which could be utilized to pick up light objects. Can the method of creating static electricity by friction be utilized to create a practical voltage? Yes! Fig. 3-8 shows the Van de Graaff artificial lightning generator. The silk belt is driven at a high velocity by a motor geared to P1. The right side of the belt is positive and passes close to the metal plate that is tied to ground. The plate has small hairlike follicles that allow electrons to be drawn up from ground and deposited on the left side of the belt. These electrons are transported up into the metal sphere where they are deposited on the metal sphere via the transfer plate, which is similar in construction to the metal plate. When the sphere is thus negatively charged it represents a very high potential difference from the objects in the surrounding area. It is then used for ex-

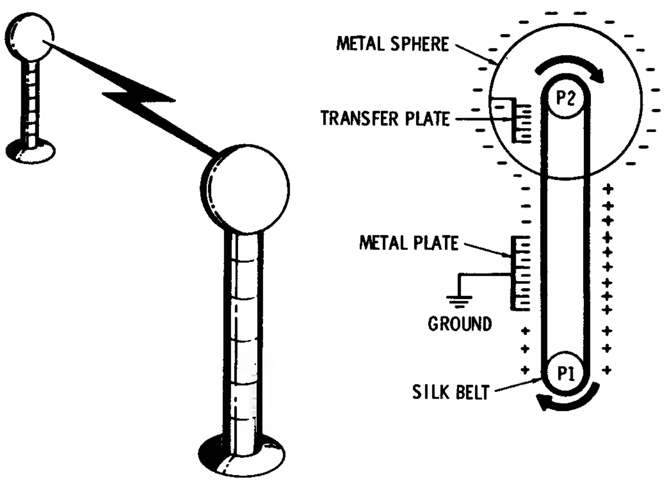


Fig. 3-8. Artificial lightning from the Van de Graaff generator.

periments involving the use of artificial lightning and for other experiments where high voltages are required.

Heat

Fig. 3-9 shows another method of generating a difference of potential. A copper wire and an iron wire are twisted together (they may be any two different conductors). Heat is then applied to them and a voltage is generated at their

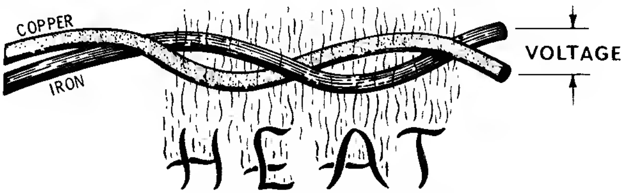


Fig. 3-9. The thermocouple.

ends. This voltage is very small but may be used in certain control operations. The arrangement is called a *thermocouple,* and it is often used in commercial thermostats.

Pressure

The method of applying pressure to a quartz crystal to create a voltage is called the *piezoelectric effect* and is shown in Fig. 3-10. Note that pressure in the horizontal plane causes a potential difference in the vertical plane. The resultant voltage is very small.

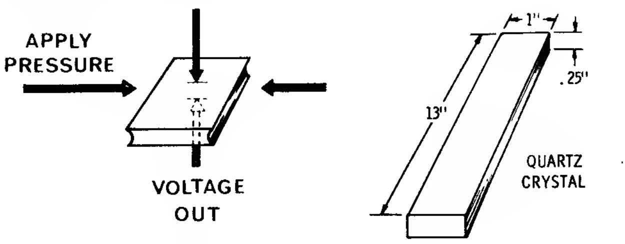


Fig. 3-10. Piezoelectric effect.

Q3-5. Two different wires twisted together and heated are called a ________.

Q3-6. The crystal pickup of a phonograph is an example of the ________ effect.

Your Answers Should Be:

A3-5. Two different wires twisted together and heated are called a **thermocouple.**

A3-6. The crystal pickup of a phonograph is an example of the **piezoelectric** effect. The small voltage obtained through the piezoelectric effect must be amplified considerably before it can be heard through the speaker of the phonograph.

Light

With the advent of the space age this method of generating voltage has really come into its own. Certain materials will generate a voltage when exposed to the sun's rays. On the ground this method is limited by the cycles of night and day and overcast weather. However, in space these problems do not exist. A spacecraft like that shown in Fig. 3-11 will

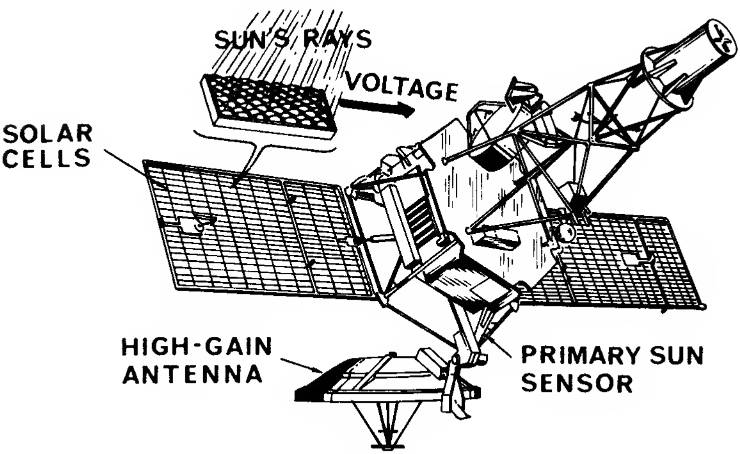


Fig. 3-11. Photoelectric effect.

have a multitude of solar cells attached to movable wings. A sun sensor will continuously point at the sun and in doing so adjust the position of the wings so that they constantly appear at right angles to the rays of the sun. The combined voltages of all the solar cells will furnish the power for the various electronic systems in the vehicle.

Chemical

Another method of generating electrical energy is through the use of chemical energy. Fig. 3-12 shows a simple voltaic cell of the type invented by Alessandro Volta in 1789. He noticed that if two dissimilar metals were placed in an acid solution a potential difference existed between them. He further noted that if a wire were connected between them

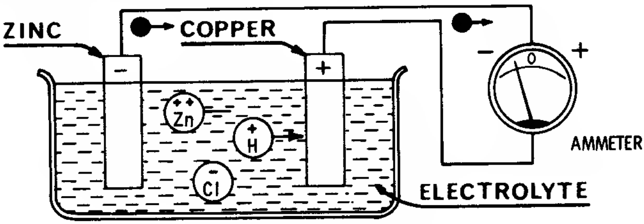


Fig. 3-12. Voltaic cell.

there was current in the wire. When hydrochloric acid is poured into water, the resultant solution is called an *electrolyte*—that is, a solution that contains ions. In this case we have positive ions, Hydrogen (H+), and negative ions, Chlorine (Cl−). When the copper and zinc electrodes are placed in this solution, the zinc dissolves. As the zinc atom enters the solution it leaves two electrons behind which makes the zinc atoms positive and the zinc electrode negative. The positive zinc ions repel the positive hydrogen ions forcing them back to the copper electrode where they capture an electron and are bubbled off as gaseous hydrogen. With an excess of electrons at the zinc electrode and a sparsity of electrons at the copper electrode there will be a current which will register on the ammeter. This process continues until the zinc strip completely dissolves. The electromotive force developed by this cell is approximately 1 volt and does not depend on the size of the cell but rather on the materials.

Q3-7. Light energy is converted into electrical energy in a __________ __________.

Q3-8. A solution that contains ions is called an ________.

Q3-9. The voltaic cell converts __________ energy into __________ energy.

Your Answers Should Be:

A3-7. Light energy is converted into electrical energy in a **solar** cell.

A3-8. A solution that contains ions is called an **electrolyte.**

A3-9. The voltaic cell converts **chemical** energy into electrical energy.

Almost any two dissimilar metals can be used for this type of cell. However, there is a distinct drawback that stems from the fact that many of the hydrogen bubbles tend to cling to the copper electrode, thus forming a barrier that rejects the hydrogen ions in the solution and stops the reaction. The action is called *polarization* and may be prevented by using a carbon rod instead of the copper and placing the rod in a porous cup containing manganese dioxide. The cup doesn't prevent the bubbles from forming but the atoms of hydrogen combine with the maganese dioxide. The manganese dioxide is called a *depolarizer*. Another disadvantage of this cell is that it is a wet cell and its liquid electrolyte can be spilled easily. This disadvantage is overcome by the dry cell shown in Fig. 3-13. The zinc can is the negative electrode. Lining the can is a blotter soaked with electrolyte. In the center is the carbon rod that serves as the positive

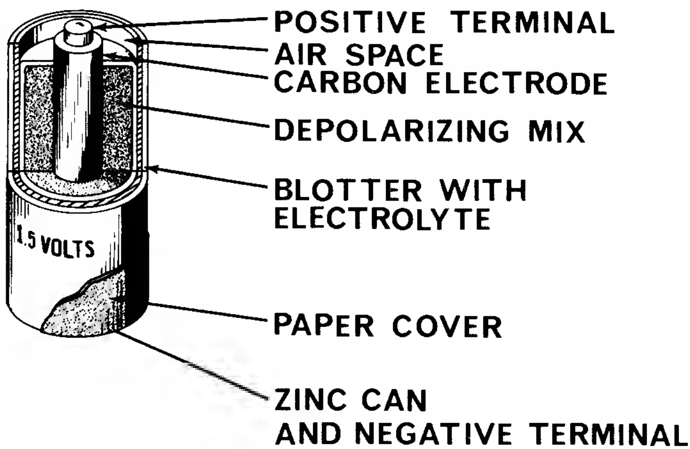


Fig. 3-13. The dry cell.

electrode. It is surrounded by the depolarizing mix which carries both sal ammoniac (a combination of ammonia and chlorine) which serves as an electrolyte, and manganese dioxide which serves as the depolarizing agent. The air space allows for the collection of gases generated in the cell. Wax or pitch seals the top of the can which has a metal cap to serve as the positive electrode. The entire cell is enclosed in a cardboard container. The cell generates approximately 1.5 volts. This type of voltage source can be used only when small amounts of current are required, as in flashlights and transistor radios.

Magnetic

The most common method of generating large voltages is by rotating a coil of wire through a magnetic field, as seen in Fig. 3-14. This method is commonly used wherever electrical power is required.

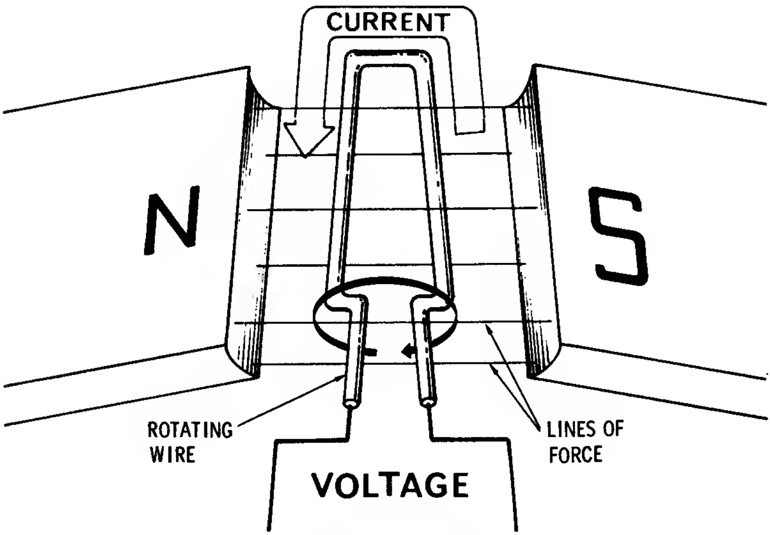


Fig. 3-14. Magnetism + motion = emf.

Q3-10. In a dry cell manganese dioxide is used to prevent ________.

Q3-11. The generator in a car is an example of changing ________ energy into ________ energy.

Your Answers Should Be:

A3-10. In a dry cell manganese dioxide is used to prevent **polarization.**

A3-11. The generator in a car is an example of changing **mechanical** energy into **electrical** energy.

Let us examine the factors that affect current generation through this method. Fig. 3-15 shows a magnetic field with two wires moving through it. Note that the direction of motion of the wire determines the direction of the current.

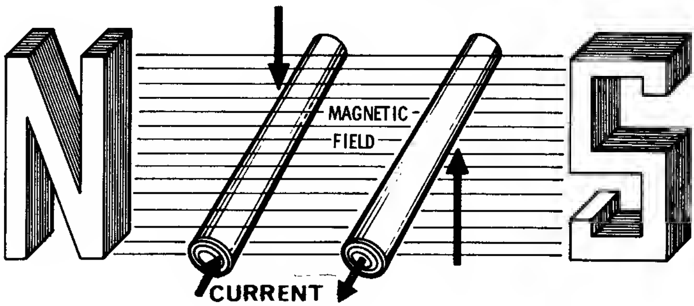


Fig. 3-15. Direction of motion affects direction of current.

In Fig. 3-16 you can see that the direction of motion affects the amount of current generated. The first wire shown is moving parallel to the lines of force and therefore does not cut through any of the lines of force. The resultant current is zero. The next wire moves perpendicularly to the lines of force and generates a maximum current. The third wire moves at an angle θ to the lines of force. The closer this angle is to 90 degrees, the greater is the current generated.

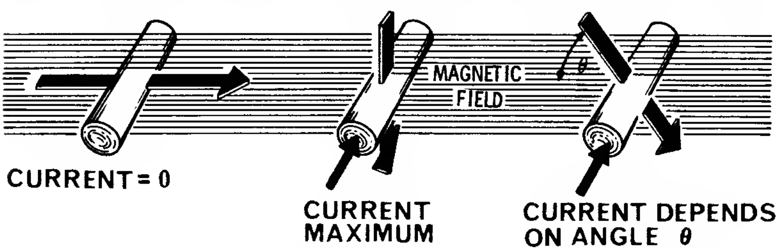


Fig. 3-16. Direction of motion affects amount of current.

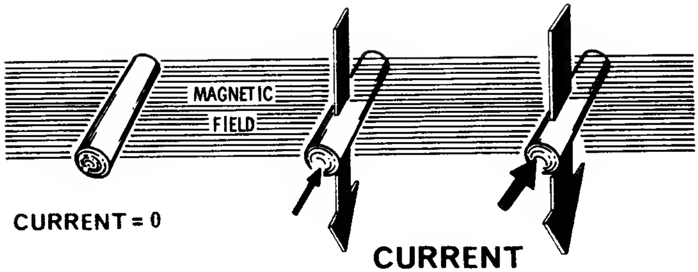


Fig. 3-17. Speed of motion affects amount of current.

Another factor affecting the amount of current generated is the speed of motion, as shown in Fig. 3-17. With no motion at all, the current generated is zero. As the speed is increased, current is generated. The amount of current depends on the number of lines of force cut in a unit of time. Thus, if the speed is increased, there will be more current.

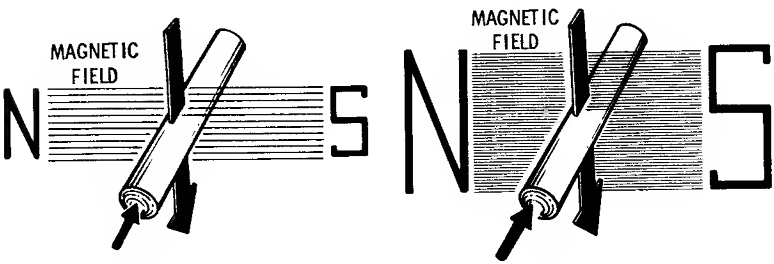


Fig. 3-18. Density of magnetic field affects amount of current.

In a similar fashion Fig. 3-18 shows the result of increasing the strength, and therefore the density, of the magnetic field. Two wires moving at the same speed through these fields will generate different amounts of current, since the wire on the right in the illustration will cut more lines of force per unit time than the one on the left.

Q3-12. The factors affecting the amount of current generated by a wire moving in a magnetic field are ________, ________, and ________.

Q3-13. Maximum current is generated when the wire moves at an angle of ________ degrees to the lines of force.

Your Answers Should Be:

A3-12. The factors affecting the amount of current generated by a wire moving in a magnetic field are **direction (of motion), speed,** and **density of magnetic field.**

A3-13. Maximum current is generated when the wire moves at an angle of **90** degrees to the lines of force.

Fig. 3-19 shows two wires moving through fields of equal density at the same speed, yet the current induced in the wires moves in opposite directions. Can you see why this is

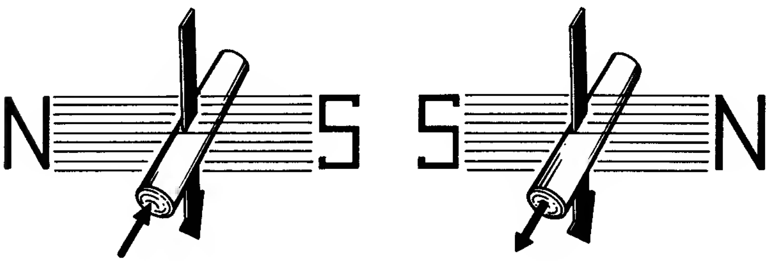


Fig. 3-19. Location of north and south poles affects current direction.

so? Note that in one instance the wire moves through a field with the north pole on the left and south pole on the right, while in the other case the fields are reversed. Thus you see that the direction of current is also dependent on the location of the north and south poles. Now let us consider what happens as a wire makes a circular path through a

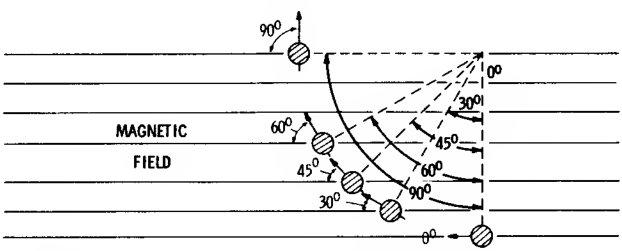


Fig. 3-20. Angles assumed as wire rotates in magnetic field.

magnetic field. Fig. 3-20 shows various positions of the wire as it rotates through its first 90 degrees. We know now that the amount of current induced in the wire when its direction is 0 degrees with respect to the magnetic field will be 0. We further know that when the angle is 90 degrees we will in-

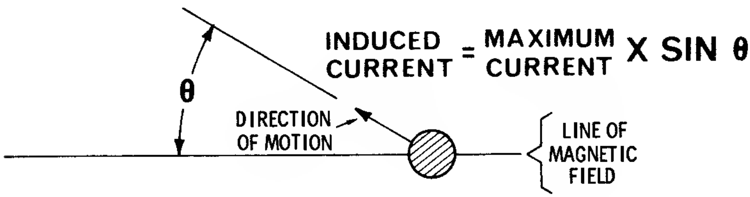


Fig. 3-21. Induced current depends upon sine of angle.

duce a maximum current. Between the zero and maximum values the current induced will depend on the angle, as shown in Fig. 3-21. That is, the induced current is equal to the maximum current multiplied by the sine of θ (theta), which is the angle that the wire makes with the magnetic field. To better understand this concept a brief review of simple trigonometry follows.

Trigonometry

Trigonometry is the branch of mathematics that considers the measurement of the angles and sides of triangles. For our purposes we will consider only those triangles that have a 90-degree angle. We will be concerned with the ratios of the various sides in these triangles to each other. The three ratios of concern to us will be those called *sine, cosine,* and *tangent.* It will be found that these ratios for a particular angle do not change no matter what the length of the sides of the triangle are. It is this fact that makes them such powerful tools in the study of electronics.

Q3-14. If the current induced at 90 degrees is 3 amperes and the sine of θ (30 degrees for this problem) is 0.5 what is the current induced at 30 degrees? Show work.

Q3-15. The three significant ratios that we will study in trigonometry are __________, __________, and __________.

Your Answers Should Be:

A3-14. The formula shown in the previous illustration shows that the current induced is equal to the product of the maximum current induced and the sine of θ. In the problem the value of the current induced at 90 degrees is given as 3 amperes. This is the same as the maximum current. The sine of the angle θ is given as 0.5. Thus the current induced at 30 degrees is 3×0.5 or **1.5 amperes.**

A3-15. The three significant ratios that we will study in trigonometry are **sine, cosine,** and **tangent.**

Sine—This ratio is shown in Fig. 3-22. Let us review some of the terminology of triangles. First consider the legs of the triangle. They are the sides that include the right angle. The third side of the triangle, the one opposite the

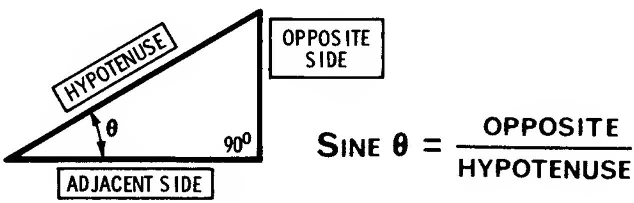


Fig. 3-22. The sine function.

right angle is called the *hypotenuse.* If we select either of the other angles and call it arbitrarily θ (as in the illustration), then we refer to the leg opposite angle θ as the opposite side. The leg that encloses the angle θ is then the adjacent side. The hypotenuse retains its name no matter which angle is selected. If the other angle is selected then its oppo-

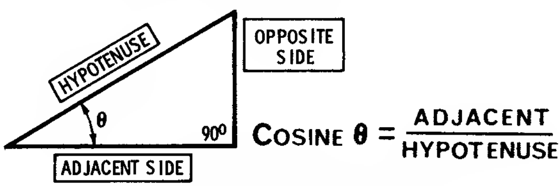


Fig. 3-23. The cosine function.

site side becomes the adjacent side of the angle θ shown in the illustration. The sine of the angle θ is given as the ratio of the length of the opposite side to the length of the hypotenuse. This is abbreviated $\sin\theta = \frac{\text{opp}}{\text{hyp}}$.

Cosine—The cosine of angle θ is shown in Fig. 3-23. It is given as the ratio of the adjacent side to the hypotenuse. This is abbreviated as $\cos\theta = \frac{\text{adj}}{\text{hyp}}$.

Tangent—The tangent of the angle θ is shown in Fig. 3-24. It is the ratio of the opposite side to the adjacent side and is abbreviated $\tan\theta = \frac{\text{opp}}{\text{adj}}$.

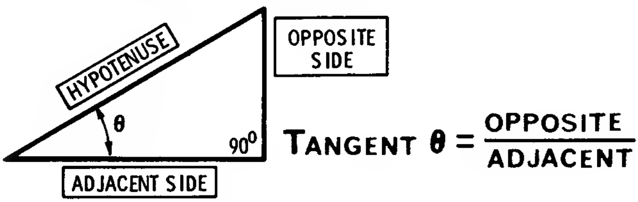


Fig. 3-24. The tangent function.

Common Sine Functions—Since we will initially be concerned with the sine of the angle let us generate a simple table of these functions. Fig. 3-25 shows a 30-60-90-degree triangle whose sides are of the lengths shown. From this triangle we get two of the ratios—sine 30 degrees and sine 60 degrees.

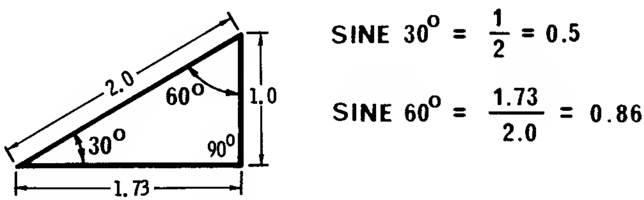


Fig. 3-25. Sine functions of 30 degrees and 60 degrees.

Q3-16. In the triangle above compute cos 30 degrees = ________.

Q3-17. Compute tan 30 degrees = ________.

Q3-18. The sine of 30 degrees and the cosine of ________ are equal.

Your Answers Should Be:

A3-16. Cos 30 degrees $= \frac{\text{adj}}{\text{hyp}} = \frac{1.73}{2.0} = 0.86.$

A3-17. Tan 30 degrees $= \frac{\text{opp}}{\text{adj}} = \frac{1.0}{1.73} = 0.58.$

A3-18. The sine of 30 degrees and the cosine of 60 degrees are equal.

You now have some facility with calculating trigonometric functions. This familiarization is all that is needed, as values for these functions are usually obtained from prepared tables. Such a table is shown in Fig. 3-26. It contains some of the most often used sine functions.

ANGLE	SINE	ANGLE	SINE	ANGLE	SINE	ANGLE	SINE
0°-360°	0			180°	0		
30°	0.5	120°	0.86	210°	0 -0.5	300°	-0.86
45°	0.707	135°	0.707	225°	-0.707	315°	-0.707
60°	0.86	150°	0.5	240°	-0.86	330°	-0.5
90°	1.0			270°	-1.0		

Fig. 3-26. Table of common sine functions.

ALTERNATING CURRENT

We can now return to the rotating wire and calculate current values at various angles of rotation. Fig. 3-27 shows the first 90 degrees of the rotation. To simplify matters let us consider that the maximum current induced is 1 ampere. Thus the current induced will be equal to the sine of the angle. Five points have been selected. From the table shown in Fig. 3-26 obtain the values of sine 0 degrees, 30 degrees, 45 degrees, 60 degrees, and 90 degrees. The result is the

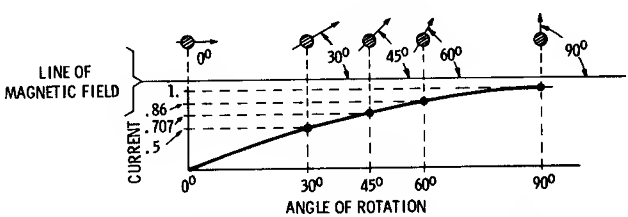


Fig. 3-27. Current variation with angle of rotation.

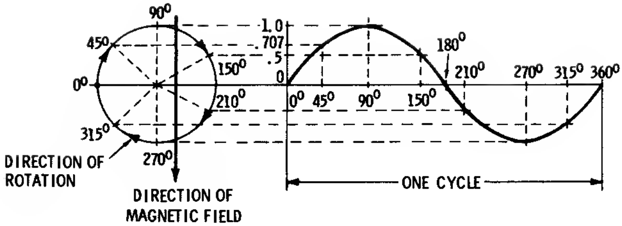


Fig. 3-28. Generation of sine wave.

curve shown in the illustration. Now consider the rest of the rotation through 360 degrees. From Fig. 3-28 we can see how some of the points are placed on a graph. The horizontal axis is a plot of the angle of rotation while the vertical axis is a plot of the current. The curve starts at 0 degrees whose sine is 0. The next point is at 45 degrees whose value from the table is 0.707. Then 90 degrees whose value is 1.0, 150 degrees whose value is 0.5, and then 180 degrees whose value is 0 since the wire is again moving parallel to the magnetic field. From this point the wire is moving through the field in the opposite direction and the resultant current is negative from 180 degrees through 360 degrees. The current alternates from positive to negative and is known as *alternating current.* Since this curve varies as the sine of the angle it is known as a *sine wave.* The plot of current from 0 degrees to 360 degrees is known as one cycle. Fig. 3-29 shows some of the nomenclature associated with a sine wave. As you will see it is common to other wave forms, too.

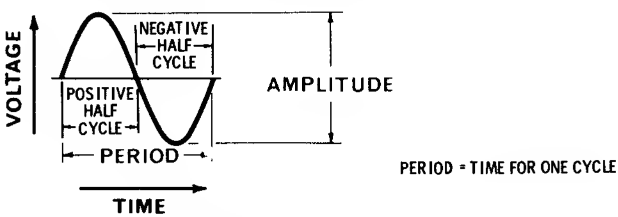


Fig. 3-29. Sine wave nomenclature.

Q3-19. The vertical height of the waveshape is the ________.

Q3-20. The time it takes for one cycle is known as the ________.

Q3-21. ________ is measured along the horizontal axis.

Your Answers Should Be:

A3-19. The vertical height of the waveshape is known as the **amplitude.**

A3-20. The time it takes for one cycle is known as the **period.**

A3-21. **Time** is measured along the horizontal axis.

Note that the amplitude of the waveshape may be representative of either voltage or current. Further note that the positive portion of the wave is known as the positive half-cycle and the negative as the negative half-cycle.

Frequency

Frequency is a measure of the number of cycles that take place in one second. For example, Fig. 3-30 shows one wave that completes a cycle in one second. The frequency of this

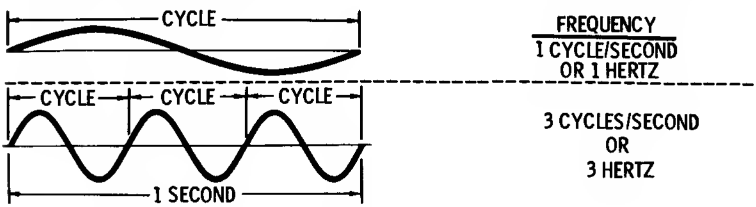
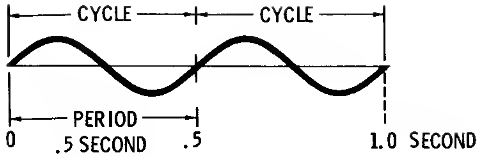


Fig. 3-30. Number of cycles per second is called frequency.

sine wave is said to be 1 cycle per second, more recently called 1 *hertz.* Beneath this sine wave is one that completes 3 cycles in the same time. Its frequency would be 3 hertz.

Frequency Versus Period

Fig. 3-31 shows the relationship between frequency and period. Two cycles of a 2-Hz waveshape are shown. The period is therefore 0.5 second as shown. Thus the frequency is equal to the reciprocal of the period or $1 \div 0.5 = 2$ hertz. Since most of the periods we will deal with will be in the order of thousandths and millionths of a second and many of the frequencies will be in the order of thousands and millions of hertz it is necessary to introduce some of the shorthand symbols that are used in electronics. The table



FREQUENCY = 2 CYCLES/SECOND

$$\text{FREQUENCY (f)} = \frac{1}{\text{PERIOD (T)}} = \frac{1}{.5\ \text{SEC}} = 2\ \frac{\text{CYCLES}}{\text{SECOND}}$$

Fig. 3-31. Relationship of frequency to period.

in Fig. 3-32 shows some of the most often used prefixes and their abbreviations. Two of the prefixes we will use very often when dealing with frequencies are k and M—as in kHz (kilohertz) and MHz (megahertz).

PREFIX	GIGA	MEGA	KILO	DECI	MILLI	MICRO	NANO	PICO
ABBREVIATION	G	M	k	d	m	μ	n	p
MULTIPLIER	10^9	10^6	10^3	10^{-1}	10^{-3}	10^{-6}	10^{-9}	10^{-12}

Fig. 3-32. Commonly used prefixes.

Q3-22. If 20 sine waves are completed in 4 seconds the frequency of the sine wave is __________. Period __________.

Q3-23. The period of a sine wave is 4 milliseconds. The frequency is __________.

Q3-24. The frequency of a sine wave is 500 kHz. The period is __________ microseconds. __________ milliseconds.

Your Answers Should Be:

A3-22. If 20 sine waves are completed in 4 seconds the frequency of the sine wave is 5 **Hz.** Period 0.2 sec. F = No. of Cycles ÷ Time = 20 ÷ 4 sec = 5 cps (Hz) T = 1 ÷ F = 1 ÷ 5 Hz = 0.2 sec.

A3-23. The period of a sine wave is 4 milliseconds. The frequency is 250 **Hz.**

$$F = 1 \div 4 \text{ msec} = \frac{1}{4 \times 10^{-3} \text{ sec}} = \frac{10^{3}}{4}$$
$$= \frac{1000}{4} = 250 \text{ Hz}$$

A3-24. The frequency of a sine wave is 500 kHz. The period is 2 microseconds (μsec). 0.002 millisec.

$$T = \frac{1}{F} = \frac{1}{500 \times 10^{3} \text{ Hz}} = \frac{1}{0.5 \times 10^{6} \text{ Hz}}$$
$$= \frac{10^{-6}}{0.5} = 2\ \mu\text{sec.}$$

Note that the symbol μ is the greek letter mu.

Fig. 3-33 shows how to manipulate 1000 Hz to obtain the period of 1 millisecond. It is assumed that the student has a good working knowledge of the powers of ten.

$$T = \frac{1}{f} = \frac{1}{1000 \text{ Hz}} = \frac{1}{10^{3} \text{ Hz}} = 10^{-3} \text{ SEC} = 1 \text{ millisecond} = 1 \text{ms}$$

Fig. 3-33. Period in milliseconds.

Wavelength

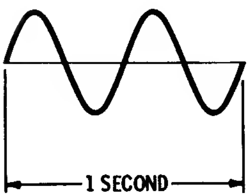
Wavelength is defined as the distance a radio wave travels in the time for one cycle. Fig. 3-34 shows the formula for this relationship. To obtain the wavelength in meters (the Greek letter lambda is used to represent wavelength) divide the velocity of radio waves in meters/sec (same as the speed of light) by the frequency in hertz. An example of such a calculation is shown in Fig. 3-35. The frequency of the wave shown is 2 Hz since two cycles take place in 1 second. The velocity of radio waves is a constant of 300,000,000 meters per second. Thus the wavelength is 150,000,000 meters. Calculations like these are used to determine the

$$\lambda \ \boxed{\text{WAVELENGTH}} \ \text{(IN METERS)} = \frac{c \ \ \boxed{\text{VELOCITY OF RADIO WAVES}} \ \text{(IN METERS/SEC)}}{f \ \ \boxed{\text{FREQUENCY}} \ \text{(IN HERTZ)}}$$

LAMBDA

Fig. 3-34. The wavelength of a radio wave is the distance the wave travels in the time for one cycle.

proper lengths for antennas. Most antennas are cut to either half- or quarter-wavelengths for the transmitted frequency. For example, the frequency of television Channel 2 (upper end) is 60 MHz. Its wavelength would be 300,000,000 meters/sec ÷ 60 MHz = 5 meters. If the antenna were cut to a half-wavelength it would be 2.5 meters long. By folding it



$$\lambda = \frac{300,000,000 \text{ METERS/SEC}}{2\text{Hz}}$$

$$= 150,000,000 \text{ METERS}$$

Fig. 3-35. Wavelength—sample calculation.

in half you would have an antenna of about 1.25 meters long which is about 4.1 feet long. A glance at your television antenna will verify this.

Q3-25. The distance that a wave travels in the time for one cycle is called ________.

Q3-26. If the frequency in the formula for wavelength is given in kHz then the wavelength will be in ________.

Q3-27. Channel 2 has a frequency range of 54 to 60 MHz and Channel 7 has a frequency range of 174 to 180 MHz. Channel ________ will require the shorter antenna.

Your Answers Should Be:

A3-25. The distance that a wave travels in the time for one cycle is called **wavelength.**

A3-26. If the frequency in the formula for wavelength is given in kHz then the wavelength will be in **millimeters.**

A3-27. Channel 2 has a frequency range of 54 to 60 MHz and channel 7 has a frequency range of 174 to 180 MHz. Channel 7 will require the shorter antenna. That is, the higher the frequency, the shorter the period. The shorter the period the shorter the distance traveled in the time for one cycle (wavelength) and the shorter the antenna.

Voltage and Current Measurement

Until now we have spoken mainly about the time relationships in the sine wave. Now let us concern ourselves with the methods of measuring the voltage and current of the sine wave. The following measurements work equally well with voltage and current. Only the instruments used will vary.

Peak Voltage—As shown in Fig. 3-36, this peak voltage is the same as E_{MAX} (or I_{MAX} in a current waveform). It is

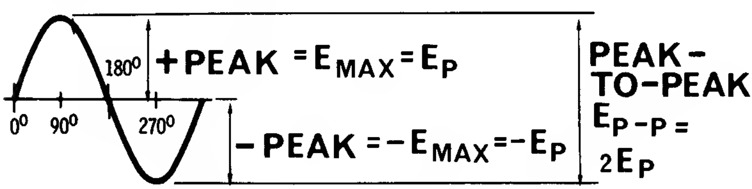


Fig. 3-36. Peak and peak-to-peak voltages.

therefore the maximum voltage of the sine wave (half-cycle). The voltage measured from this positive peak to the negative peak is known as the peak-to-peak voltage, and in a sine wave of the type we have been discussing it would be equal to twice the maximum voltage of one half-cycle. Peak-to-peak voltages can be measured visually on an in-

strument called an oscilloscope, and on some voltmeters that have a scale that is appropriately calibrated.

Average Voltage—The concept of average voltage is best shown through the use of a simpler waveform than the sine wave. Such a waveform is the square wave, shown in Fig. 3-37. In this square wave you see a constant positive 4 volts

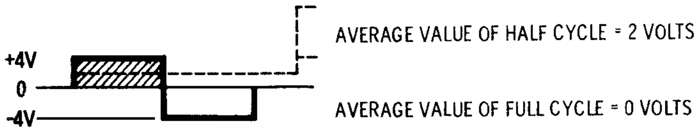


Fig. 3-37. Average value of a simple square wave.

for half a cycle and a constant negative 4 volts for half a cycle. This square wave is similar to the voltage we would obtain if we were to run a direct current (say from a 4-volt battery) through a circuit for a short period of time and then run it through in the reverse direction (thus obtaining the negative half-cycle). It is obvious upon inspection that the average voltage for a full cycle of such a waveform is zero, providing the time for each half cycle is the same.

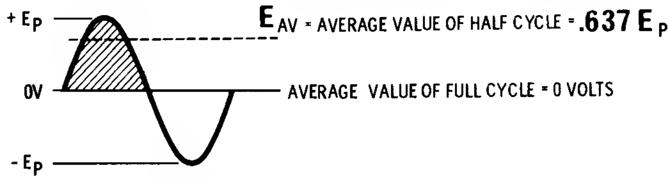


Fig. 3-38. Average value of a sine wave.

However, the average voltage for the positive half-cycle will be +2 volts. In Fig. 3-38 see a sine wave whose average full-cycle voltage is also zero. However, because the half-cycles are not composed of constant voltages, the average voltage for a half-cycle of a sine wave will turn out to be 0.637 of the peak voltage, instead of half the peak voltage as in the square wave.

Q3-28. If the maximum voltage of a sine wave is 7 volts, the peak-to-peak voltage is ________.

Q3-29. If the peak voltage of a square wave is 8 volts, the average full-cycle voltage is ________.

Your Answers Should Be:

A3-28. If the maximum voltage of a sine wave is 7 volts the peak-to-peak voltage is **14 volts.**

A3-29. If the peak voltage of a square wave is 8 volts, the average full-cycle voltage is **zero.**

Effective Voltage—To understand the nature of effective voltage it is necessary to remember that when there is a current through a wire, heat is generated (Fig. 3-39). Your toaster and electric iron are applications of this phenome-

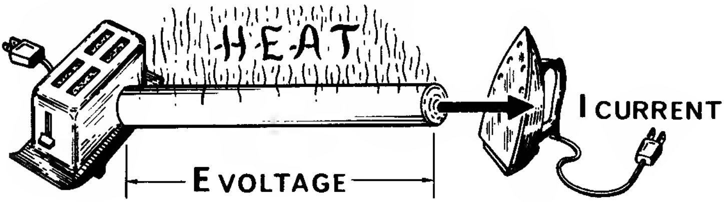


Fig. 3-39. Current through wire generates heat.

non. This heat is not always desirable as you may have noticed if you have touched an electric light bulb after it had been on for some time. In talking about a d-c voltage you will find that all of the current drawn from the battery will be utilized *effectively* to generate heat. In a sine wave however, the voltage at any instant (*instantaneous voltage* due to an instantaneous current) is changing. Thus the heat generated at any instant is different. Thus, it is found that the effective current of a sine wave is 0.707 of the peak current (Fig. 3-40). That is, a sine wave whose peak current is 1 ampere will have the same heating effect as a d-c current of 0.707 amperes. Most instruments like the voltmeter and ammeter are designed to measure effective values.

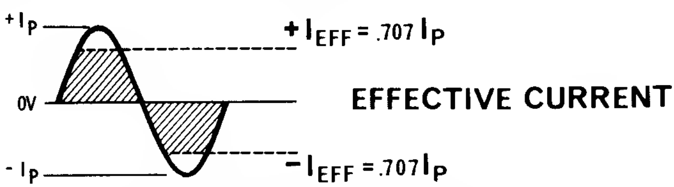


Fig. 3-40. Effective current value of a sine wave.

POWER

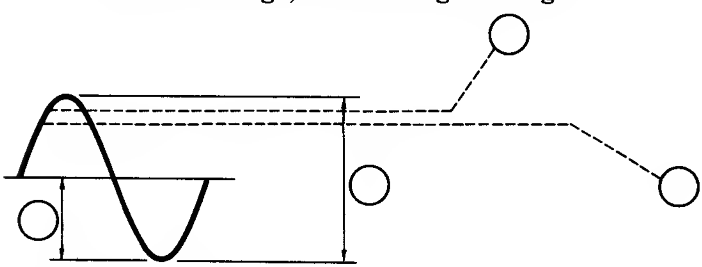
As you have seen, current passing through a wire generates heat. The amount of heat generated could be measured thermally if we so desired. It is more important to calculate the amount of power generated in terms of *watts*. One watt is the amount of power generated when a voltage of 1 volt causes a current of 1 ampere (Fig. 3-41). For the purposes

$$P \begin{matrix}\text{POWER}\\ \text{(WATTS)}\end{matrix} = E \begin{matrix}\text{VOLTAGE}\\ \text{(VOLTS)}\end{matrix} \times I \begin{matrix}\text{CURRENT}\\ \text{(AMPERES)}\end{matrix}$$

Fig. 3-41. Power equals voltage times current.

of a-c voltages, the voltages and currents used will be the effective values. In the next chapter you will learn more of the nature of power in your studies of resistors and Ohm's law.

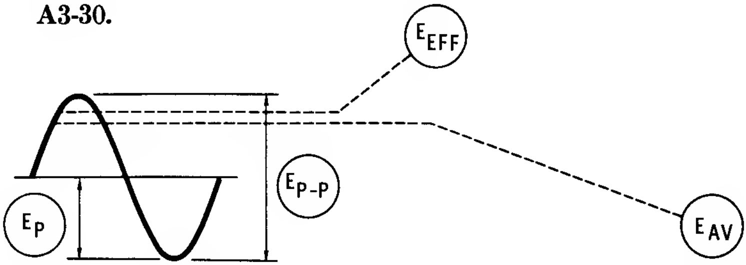
Q3-30. In the accompanying illustration identify the following: peak voltage, peak-to-peak voltage, effective voltage, and average voltage.



Q3-31. A 240-watt bulb is connected to a 120-volt line; the current drawn is ________ amperes.

Your Answers Should Be:

A3-30.



A3-31. A 240-watt bulb is connected to a 120-volt line; the current drawn is 2 amperes.
P(240 watts) = E(120 volts) × I(2 amperes)

SUMMARY QUESTIONS

1. When a weight is moved work is done and energy is expended.
   a. When a 6-pound weight is moved from a height of 14 inches to a height of 38 inches the work done is ______ foot-pounds.
   b. A 50-gram weight is moved ______ centimeters vertically causing an expenditure of 200 dyne-cm.
2. Electrons can be caused to move by providing a difference in potential between two points. Work is done and energy is expended when electrons are moved.
   a. Difference in potential is measured in ______.
   b. If 20 joules of energy are expended in moving 4 coulombs of electrical charge, the difference in potential is ______.
   c. When 12 coulombs of electrical charge are moved past a point in 3 seconds, the current is ______ amperes.
3. Voltage may be generated in several different ways. All of these ways depend on the conversion of one type of energy (heat, light, or mechanical, for example) to electrical energy. Some of the methods used have limited applications (heat, pressure, and friction, for example) while others like the chemical and magnetic methods are used to supply primary power to much of the electronic equipment in use today.

a. A solar battery converts ________ energy to ________ energy.
b. Your car battery changes ________ energy to ________ energy.
c. A maximum current is induced in a wire when it moves (parallel, perpendicular) to the magnetic lines of force.
d. The induced current at any instant is equal to the product of the maximum current and the ________.

4. Rotating a wire through a magnetic field causes a current through the wire first in one direction and then in the other. This is called an alternating current and because its instantaneous current is proportional to the sine of the angle of rotation, it is called a sine wave.
   a. If the period of a sine wave is 4 milliseconds its frequency is ________ hertz.
   b. The distance that a wave travels in the time for one cycle is called the ________.
   c. List the following voltages associated with a sine wave in order according to magnitude (largest first) : peak, effective, peak-to-peak, and average.

SUMMARY ANSWERS

1a. When a 6-pound weight is moved from a height of 14 inches to a height of 38 inches the work done is **12** foot-pounds. ($38'' - 14'' = 24'' = 2' \therefore 2' \times 6$ lbs $= 12$ ft-lbs)

1b. A 50-gram weight is moved 4 centimeters vertically causing an expenditure of 200 dyne-cm.

2a. Difference in potential is measured in **volts.**

2b. If 20 joules of energy are expended in moving 4 coulombs of electrical charge, the difference in potential is **5 volts.**

2c. When 12 coulombs of electrical charge are moved past a point in 3 seconds, the current is 4 amperes.

3a. A solar battery converts **light** energy to **electrical** energy.

3b. Your car battery changes **chemical** energy to **electrical** energy.

3c. A maximum current is induced in a wire when it moves **perpendicular** to the magnetic lines of force.

3d. The induced current at any instant is equal to the product of the maximum current and the **sine** θ.

4a. If the period of a sine wave is 4 milliseconds its frequency is **250** hertz.

4b. The distance that a wave travels in the time for one cycle is called the **wavelength.**

4c. **Peak-to-peak, peak, effective, average.**

4

Resistive Circuits

What You Will Learn

In this chapter you will learn about the basic circuit principles which can be used to explain virtually every electronic circuit you will come in contact with from now on. The manner in which current is developed in a simple circuit containing resistance and a source of voltage is explored, and the laws of Ohm and Kirchhoff are discussed in great detail. Much of the chapter will be devoted to using these laws in the solution of series and parallel circuits.

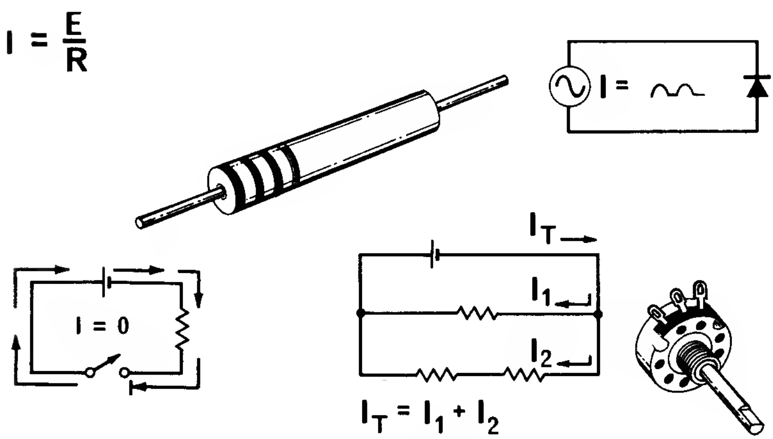


Fig. 4-1. Basic circuit principles.

BASIC CIRCUIT PRINCIPLES

Let us consider what is meant by a circuit. We would like to put the electrical energy at our command to work. To do this we must have a source of *voltage*, an object to work on (referred to as a *load*), and a method of delivering the electrical energy to the load.

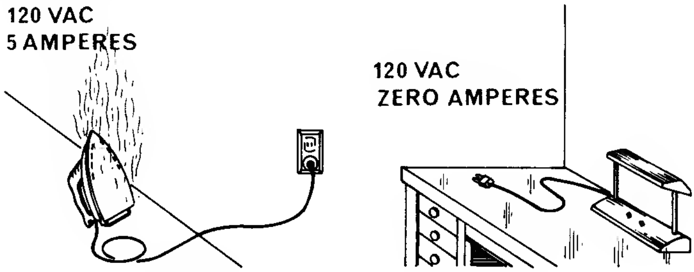
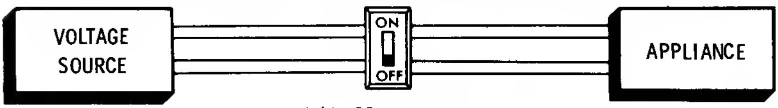
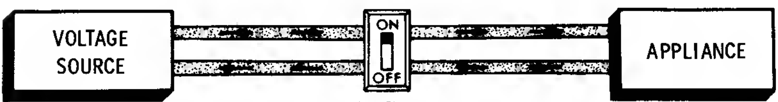


Fig. 4-2. Current delivered to a load.

Fig. 4-2 shows a typical source of voltage found in every home: the electrical outlet that delivers approximately 120 volts of alternating current. Next to it is a lamp which is not on because it has not been plugged into the outlet. That is, we have not provided a path for the electrical energy to reach the light. No current is delivered and no energy may



(*A*) *No current.*



(*B*) *Current.*

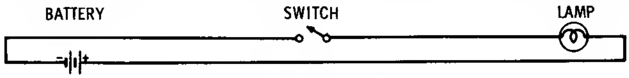
Fig. 4-3. A switch used to complete a circuit.

be expended in the load (the lamp). The left-hand side of this figure shows an iron plugged into the outlet. A current of 5 amperes is delivered and the electrical energy is transferred to the load (the iron) and expended as heat energy. Note that the method of delivering the electrical energy is to provide a path for current to the load and back to the source.

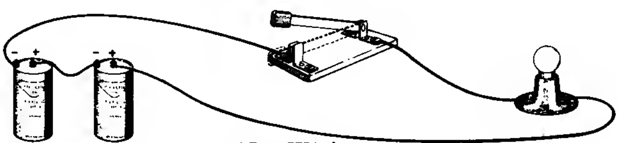
Fig. 4-3 shows another element of a complete circuit: the switch. A typical wall unit is shown that is usually arranged so that it activates the wall outlets in a room. An appliance, such as a lamp or a radio, may be plugged into such a wall outlet ready to be activated as soon as the circuit is complete. This is accomplished by flipping the switch to the ON position, thus providing a path for current to the appliance and back to the source of voltage.

SIMPLE CIRCUIT ANALYSIS

A simple circuit is shown in Fig. 4-4. It consists of two cells, a switch, and a lamp. Instead of drawing the objects in a *wiring* diagram (Fig. 4-4B), it is much simpler to draw symbols that represent the components in a circuit. Such a drawing is shown in Fig. 4-4A, and is called a *sche-*



(*A*) *Schematic.*



(*B*) *Wiring.*

Fig. 4-4. Comparison of diagrams.

matic diagram. As we discuss new components we will introduce corresponding symbols for use on schematic diagrams. In Fig. 4-4 the two 1.5-volt dry cells are the source of voltage, the load is the lamp, and the switch controls the current to the load.

Q4-1. The object in a circuit that utilizes the electrical energy is called the ________.

Q4-2. There is no current in the circuit of Fig. 4-4 because it is not a (an) ________ circuit.

Q4-3. A diagram that shows symbols instead of the actual objects is called a (an) ________.

Q4-4. Draw a circuit diagram of a flashlight.

Your Answers Should Be:

A4-1. The object in a circuit that utilizes the electrical energy is called the **load.**

A4-2. There is no current in the circuit of Fig. 4-4 because it is not a **complete or closed** circuit.

A4-3. A diagram that shows symbols instead of the actual objects is called a **schematic.**

A4-4. The schematic shown in Fig. 4-4A is what you should have drawn to represent a flashlight.

RESISTANCE

Definition

Resistance is the opposition offered to the current in a circuit. The lamp in the previous circuit offers an opposition to the current and therefore has the property of resistance. By definition, the larger the resistance in a circuit, the smaller the current.

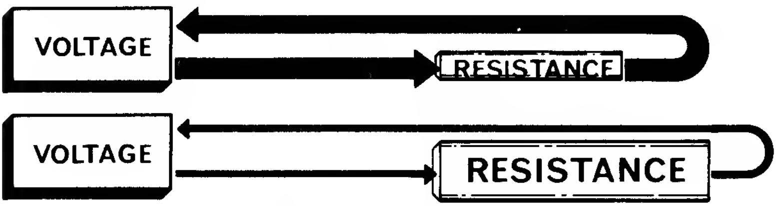


Fig. 4-5. Effect of resistance in a circuit.

Fig. 4-5 shows two circuits supplied by the same voltage source. The circuit with the greatest amount of resistance has the least amount of current. Resistance is measured in units called *ohms.*

Conductivity

In electronics you will be concerned with three types of materials. These materials are classified according to their ability to "allow the passage of" (*conduct*) electricity. Those that pass electricity readily are known as *conductors.* Materials with many free electrons fall into this category. Silver, platinum, and copper are some that you will find used

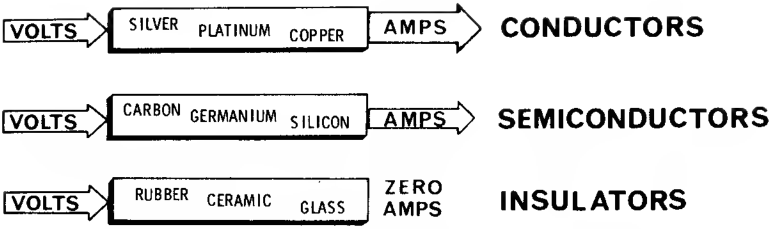


Fig. 4-6. Conductors, semiconductors, and insulators.

to make up the wires that connect the various components in a circuit. They offer very little opposition to current—that is they have little resistivity (resistance).

The materials in the next class tend to *impede* the current in a circuit. Materials such as germanium, silicon, and carbon are called *semiconductors,* and they are used in the manufacture of diodes, transistors, and *resistors.* These components all have the ability to regulate the current in a circuit. They accomplish this by varying the amount of *resistance* (also called *impedance*) in a circuit.

The next class of materials prevents the flow of electricity in a circuit. They are called *insulators.* Rubber, ceramic, and glass materials fall into this class and are used to prevent electricity from traveling undesirable paths. A simple example of this is the insulation on the common line cord, which not only prevents you from coming in contact with the high voltage in it, but also acts to separate the wires from each other, thus keeping the current from taking a short cut back to the source (an action known as a short circuit) instead of traveling through the high resistance of the appliance.

Just as the opposition to current is measured in units of resistance called ohms so may you consider the ease with which current is passed in units of *conductance,* called *mhos.* Fig. 4-7 shows the relationship between these units.

To better understand the concept of conductivity let us consider using the nation's highways as an analogy. At

$$\underset{\text{(MHOS)}}{\text{CONDUCTIVITY}} = \frac{1}{\underset{\text{(OHMS)}}{\text{RESISTIVITY}}}$$

Fig. 4-7. Relationship of conductivity to resistivity.

5 P.M. the scene in industrial plants all over the country is the same. The parking lots are packed with cars as shown in Fig. 4-8. The full parking lot represents the pressure to be put on the roads. It is therefore analogous to the source of *voltage*. The roads are the *wires* that connect the factory to the homes (they represent the *load*). When the whistle blows (the *switch*) the circuit is complete. The cars move toward the driveway to enter the road. Although all of the cars can travel as fast as 100 miles per hour, they nevertheless can proceed only at the speed dictated by the resistance of the road.

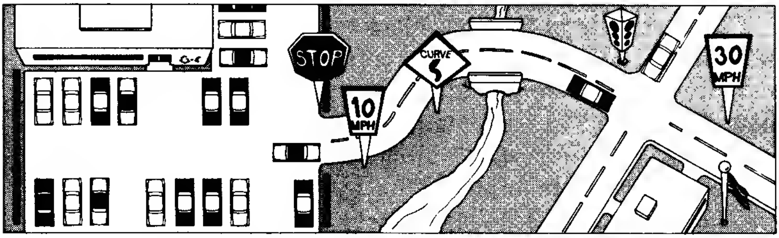


Fig. 4-8. "Resistance" and "conductance" on a highway.

What are some of the factors that govern the resistance of the road? The stop sign, the S-curve, the traffic light, and the narrow bridge all are signs that tend to slow down the vehicles. However, the speed limit signs are different. They tell the vehicles how fast they may go, and you will notice that the higher the speed limit, the lower the resistance of the road. The superhighway, for example, may have a limit of 65 mph, which must mean that it has no traffic lights, no severe curves, and plenty of traffic lanes. These speed limit signs are the same as *conductance* in an electric circuit. Thus, conductance shows the speed at which electrons may move in a circuit, while resistance shows the amount of opposition to current in a circuit.

Resistivity

Factors Determining Resistance—Resistivity is a measure of the amount of resistance offered by a specific material, and is a constant that varies with temperature. It is represented by the Greek letter rho (ρ) and is measured in units like ohm-meters or ohms per circular mil-foot. Note

$$\text{OHMS} = R = \rho \frac{l}{A} = \text{OHM-METERS} \times \frac{\text{METERS}}{\text{METERS}^2}$$

Ω (OMEGA)

$$\text{RESISTANCE} = \text{RESISTIVITY} \times \frac{\text{LENGTH}}{\text{CROSS SECTIONAL AREA}}$$

Fig. 4-9. Factors determining resistance.

that the resistance depends on not only the resistivity of the material; it will increase with the length of the component and decrease as the cross-sectional area is increased. Thus, a thin wire offers a great amount of resistance just as a narrow road will prevent a great number of cars from moving between two points. A road made from concrete allows more cars per hour to pass than a dirt road. In the same fashion the material from which the wire is made affects the resistance.

Q4-5. **The opposition offered to current in a circuit is called ________.**

Q4-6. **The unit of resistance is the ________.**

Q4-7. **Materials that pass current readily are known as ________.**

Q4-8. **Materials used to regulate the current in a circuit are called ________.**

Q4-9. **The rubber coating on a line cord is an example of the use of a (an) ________.**

Q4-10. **The unit for measuring conductance is the ____.**

Q4-11. **The speed limit signs on the highways are analogous to the electrical circuit measurement of ________.**

Your Answers Should Be:

A4-5. The opposition offered to current in a circuit is called **resistance.**

A4-6. The unit of resistance is the **ohm.**

A4-7. Materials that pass current readily are known as **conductors.**

A4-8. Materials used to regulate the current in a circuit are called **semiconductors.**

A4-9. The rubber coating on a line cord is an example of the use of an **insulator.**

A4-10. The unit for measuring conductance is the **mho.**

A4-11. The speed limit signs on the highways are analogous to the electrical circuit measurement of **conductance.**

Resistivity of Various Materials—Fig. 4-10 shows the resistivities of three types of materials. The unit of resistivity used is the ohm-centimeter which is the resistance of a wire one centimeter long whose cross-sectional area is one circular mil (mil = .001 in; circular mil = Area of .001 in^2). Approximate values are used, as we are interested in the order of magnitude of the resistivities of the three types of materials that we will come in contact with in electronics.

The first of these materials is copper, the most common, and the one used in connecting wires, almost to the exclusion of all other materials. As a material with many free electrons it has an almost minuscule resistivity of .000001 ohm-centimeters. Materials such as gold and silver have much lower resistivities but because of their high cost are used only for very special applications.

MATERIAL	RESISTIVITY	CLASSIFICATION
COPPER	10^{-6} OHM - CM	CONDUCTOR
GERMANIUM	10^{2} OHM-CM	SEMICONDUCTOR
CERAMIC	10^{14} OHM - CM	INSULATOR

Fig. 4-10. Resistivity of various materials.

The next material listed is germanium, a semiconductor, used for manufacturing diodes and transistors. Note that the resistivities are in the order of 100 ohm-centimeters for semiconductor materials. The materials used for constructing resistors (carbon and carbon composition) are in this order of magnitude. Insulators such as ceramics carry resistivities in the order of 10,000,000,000,000 ohm-centimeters. Thus, they offer an almost infinite opposition to current, compared to the other materials mentioned.

The Unit of Measurement

Resistance is measured in units called ohms. Fig. 4-11 defines the ohm as the resistance offered in a circuit that allows 1 ampere of current when a voltage of 1 volt is

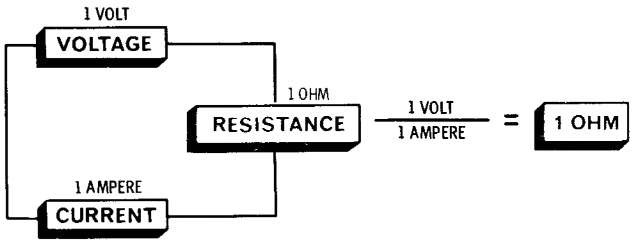


Fig. 4-11. Definition of an ohm.

applied. Another way of saying this is when 1 volt is divided by 1 ampere the result is 1 ohm. This relationship is the most important one you will study in electronics and is the basis for Ohm's law.

Q4-12. **A material with many free electrons is called a(an) ________.**

Q4-13. **A material with a resistivity of 500 ohm-centimeters would most likely be a(an) ________.**

Q4-14. **Calculate the resistance of 1000 centimeters of copper wire whose cross-sectional area is 1 square centimeter.**

Q4-15. **If it takes 10 volts to develop a current of 1 ampere in a circuit, the resistance of the circuit is ________ ohms.**

Q4-16. **If there are 20 amperes of current in a circuit with 10 volts applied, the resistance is ________.**

Your Answers Should Be:

A4-12. A material with many free electrons is called a **conductor.**

A4-13. A material with a resistivity of 500 ohm-centimeters would most likely be a **semiconductor.**

A4-14. Using the formula given in Fig. 4-9 and taking the resistivity from the table in Fig. 4-10 we have: $R = \frac{1}{A} = 10^{-6}$ ohm-cm $\times \frac{1000 \text{ cm}}{1 \text{ cm}^2}$

$$= .001 \text{ ohm}$$

A4-15. If it takes 10 volts to develop a current of 1 ampere in a circuit, the resistance of the circuit is **10** ohms. Referring to Fig. 4-11 we note that if it takes 1 volt to develop a current of 1 ampere through a resistance of 1 ohm, then it must mean that a circuit that requires 10 volts to develop a current of 1 ampere must have a resistance of 10 times as much or, in this case, 10 ohms.

A4-16. If there are 20 amperes of current in a circuit with 10 volts applied, the resistance is **0.5** ohm. That is $\frac{10 \text{ volts}}{20 \text{ amperes}} = 0.5$ ohm.

Resistor Types and Construction

Various types of resistors are used in electronics. Fig. 4-12 shows some of the most often used *fixed* resistors. A fixed resistor is one whose value may not be varied in a circuit. It is selected for a specific nonvariable function and a specific range of voltage and current conditions.

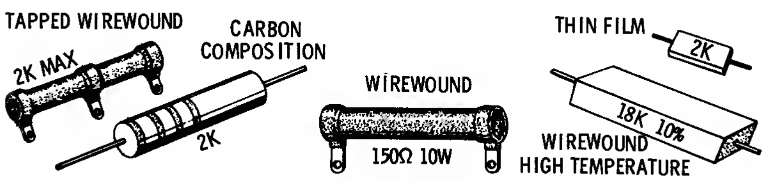


Fig. 4-12. Fixed resistors.

Fixed Composition—The most common of all resistors you will come in contact with is the carbon composition resistor. A 2000-ohm (2K) resistor of this type is shown in Fig. 4-12. The colored stripes tell its value. The use of this color coding is explained in this chapter. A simple component to construct, it has at its core a small deposit of carbon connected to the two copper leads and surrounded by an insulating material. This type of component cannot withstand high currents and it is difficult to make in exact resistance values.

Fixed Wirewound—The next most often encountered resistor is the wirewound resistor shown in Fig. 4-13. This component consists of a ceramic core around which is wound a thin copper-nickel alloy (or other moderately resistive material) wire. The wire is coated with an insulating material to prevent adjacent turns from coming in contact with each other. Metal clamps are placed at either end to serve as terminals for connection into a circuit. An enamel-coated insulation is molded over the whole assembly, leaving only the terminals exposed. This protects the wires from breakage and provides additional insulation from the surrounding circuits. The component is hollow to allow for heat dissipation. Mounting brackets may be placed inside the component as shown. The component is marked with its value and a wattage rating, which will be discussed later on in this chapter. The schematic symbol for this component is shown, and it is the same for all types of fixed resistive components.

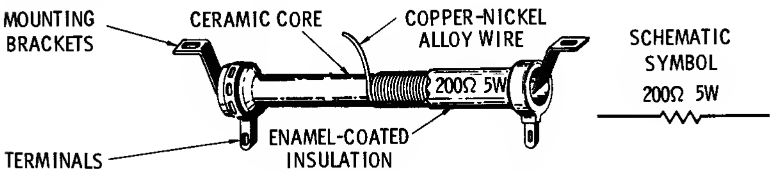


Fig. 4-13. Wirewound resistor.

Q4-17. A component whose resistance may not be varied in a circuit is called a(an) ________ resistor.

Q4-18. The most commonly used component is the ______ ________ resistor.

Your Answers Should Be:

A4-17. A component whose resistance may not be varied in a circuit is called a **fixed** resistor.

A4-18. The most commonly used component is the **carbon composition** resistor.

Tapped Resistors—Different types of wirewound resistors are available depending on the application. The 18K unit shown in Fig. 4-12 is used for high-temperature applications. The tapped wirewound resistor in Fig. 4-13 is used where a particular current division is desired in a circuit. The one shown has a flat construction and a maximum value of 2000 ohms. The tap may be placed anywhere (that is, during manufacture), depending on your needs. Center-tapping is typical. This would give you a resistance of 1000 ohms from either end to the center and 2000 ohms from end to end. Thus, by taking the output from the center-tap of such a resistor, you may select half the voltage in a particular circuit.

Thin-Film Technique—Fig. 4-14 shows the construction of a thin-film tapped resistor. As we enter the era of micro-

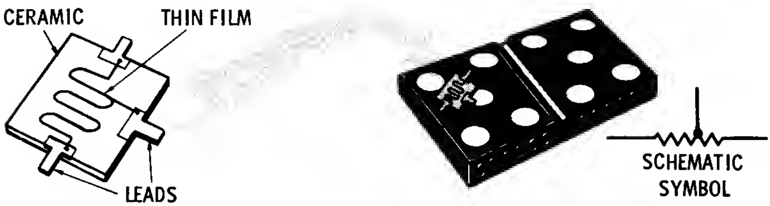


Fig. 4-14. Thin-film resistor, tapped.

electronics the need for smaller and smaller components becomes greater. One of the techniques used is the thin-film technique. Thin films (in the order of 50 to 100 *atoms* thick) are deposited on insulating substrata by a process called vacuum evaporation. The component in Fig. 4-14 is compared to a domino to give you an idea of its size (in the order of .01 inch square). Newer techniques used in the manufacture of integrated circuits may provide as many as 100 such components in the same space. The schematic symbol for

such a component is shown in the illustration. It is very difficult to construct accurate resistors using thin-film techniques. However, as you will see, the most important factor is not the actual value of a resistor but rather its value compared to other resistors in the circuit. Thin-film techniques allow us to maintain these ratios even though particular resistance values are not met. The most accurate method for obtaining exact resistances is the wirewound technique.

Color Code

First Three Bands—Values on carbon-type resistors are not marked in numbers; they are shown with colored stripes which tell us the characteristics. Fig. 4-15 shows what the stripes stand for. The colors used start with black (the absence of light) which represents zero, and end with white (the presence of all the colors of the spectrum) which represents nine. With the exception of brown and gray the rest of the colors are the light spectrum from red to violet and

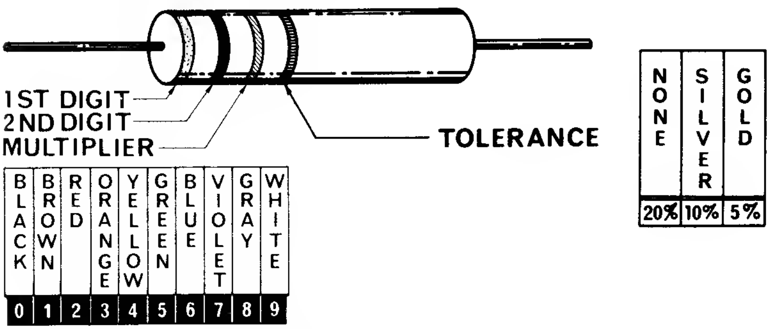
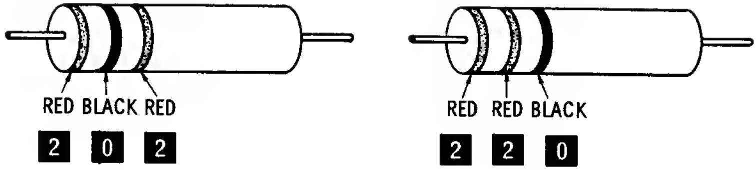


Fig. 4-15. Resistor color code.

can be committed to memory quite easily if you remember that *green* (a *five*-letter word) represents the number *five.* Facility with this code will be gained through constant usage. The first band of color on the resistor (the band right on the edge of the component no matter which way you hold it) is the first digit of the resistance value. The next band is the second digit of the resistor value. The third band is the multiplier (or the number of zeros following the second digit). Thus the component shown in Fig. 4-16A has a first digit of 2 (red), a second digit of 0 (black) and a multiplier



(*A*) *2000 ohms.* (*B*) *22 ohms.*

Fig. 4-16. The order of the colors is significant.

of 100 or two zeros following the second digit (red). Therefore its value is 2000 ohms or 2K.

The Fourth Band—Tolerance—The fourth band on a resistor is used for something called *tolerance*. As we have noted, it is difficult to make carbon-composition resistors to exact values. Thus, during manufacture the resistors are measured as they come off the assembly line. All those that are within five percent of their expected value are marked with a gold stripe, those within 10 percent of their rated value are marked with a silver stripe, and those within 20 percent of their rated value have no fourth stripe. Obviously, you pay a premium for 5- and 10-percent resistors.

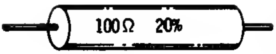
Standard Resistors—Note that not all values of carbon resistors are manufactured. Fig. 4-17 shows the standard 5- and 10-percent resistors manufactured. Note that only the 100-ohm range is shown. The significant digits will hold true for every range of resistor. For example, a 180-ohm resistor is shown in the table. There will also be a 1.8K and 18K, and a 1.8 Meg manufactured. Note that more different types of 5-percent resistors are made than 10-percent resistors. The reason for this is illustrated in Fig. 4-18. A 100-ohm resistor is shown with a tolerance of 20 percent. Resistors coming off the assembly line with these ratings will have a range of values as shown in the figure—that is, anywhere from 80 to 120 ohms. Consider a 100-ohm, 10-percent resistor. Its range would be 90 to 110 ohms, a total of 20

10% RESISTORS

100	120	150	180	220	270	330	390	470	560	680	820
110	130	160	200	240	300	360	430	510	620	750	910

5% RESISTORS

Fig. 4-17. Standard composition resistor values.



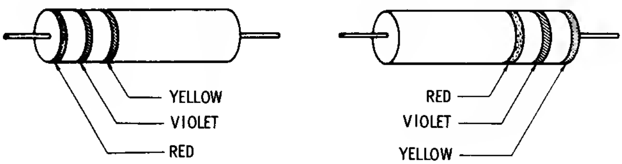
TOLER.	LOW	HIGH	RANGE
20%	80	120	40
10%	90	110	20
5%	95	105	10

Fig. 4-18. Tolerance.

ohms. The next highest resistor in the series is the 120-ohm resistor. Its range would be (based on 10 percent of 120 ohms or 12 ohms) 108 ohms through 132 ohms. Note how this overlaps the high range of the 100-ohm resistor—110 ohms. Thus, all resistor values may be taken into account using this system.

Five-percent resistors have a smaller range (10 ohms on a 100-ohm resistor) and therefore must be manufactured at closer intervals, as shown in Fig. 4-18. For special orders, resistors of 1-percent tolerance and less may be manufactured at a premium cost. Wirewound resistors are manufactured at many of the values not shown in Fig. 4-17, and at lower tolerances. The importance of the order of the colors of the resistor is shown in Fig. 4-16. Two resistors with two red bands and one black band are shown, but each has a different value.

Q4-19. Write the values of these two resistors.



Q4-20. Complete the table below.

RESIST. NO.	1ST DIGIT	2ND DIGIT	MULT.	TOLERANCE COLOR	%	VALUE	MAX. VALUE	MIN. VALUE	RANGE
1	BROWN	RED	YELLOW	SILVER					
2	BLUE	GRAY	ORANGE	—					
3	ORANGE	ORANGE	BROWN	GOLD					
4	BROWN	BLACK				1 MEG	1.1MEG		
5				SILVER				423K	

Your Answers Should Be:

A4-19. Left-270K; Right-4.7K. This is just a reminder that resistors are *not* read from left to right but rather from the color nearest to the end.

A4-20. The completed table is shown below.

RESIST.	1ST	2ND		TOLERANCE			MAX.	MIN.	
NO.	DIGIT	DIGIT	MULT.	COLOR	%	VALUE	VALUE	VALUE	RANGE
1	BROWN	RED	YELLOW	SILVER	10	120K	132K	108K	24K
2	BLUE	GRAY	ORANGE	—	20	68K	81.6K	54.4K	27.2K
3	ORANGE	ORANGE	BROWN	GOLD	5	330	346.5	313.5K	33
4	BROWN	BLACK	GREEN	SILVER	10	1 MEG	1.1MEG	0.9MEG	200K
5	YELLOW	VIOLET	YELLOW	SILVER	10	470K	517K	423K	94K

Some discussion of this table might help you understand the methods involved. The first resistor shows first and second digits of 1 and 2, respectively, followed by four zeros or 120,000 ohms, 120K. Its tolerance of 10 percent gives a ± 12K range for a maximum value of 132K and a minimum value of 108K and a range of 24K. Resistors 2 and 3 are calculated in a similar fashion except that their tolerances are 20 percent and 5 percent, respectively.

Resistor 4 requires a little more thought. Its value is given as 1 Meg; thus, it must have first and second digits of 1 (brown) and 0 (black) and a multiplier of 100,000 (five zeros), which is green, to give us 1,000,000 ohms or 1 Meg. Examining the value of 1 Meg, and the maximum value of 1.1 Meg, you can see that the difference is .1 Meg, which is 10 percent of 1 Meg. Thus, the rest of the table can be completed. Note that .1 Meg is the same as 100K.

Resistor 5 requires the most thought. The silver band indicates a 10-percent tolerance. If we consider that the minimum value is 90 percent, then we can get the actual value by dividing 423K by 90 percent to get 470K. The rest is then straightforward.

Power Considerations

You are already familiar with the fact that heat is generated when current passes through a material. The amount

Fig. 4-19. Power dissipated increases as current increases.

of heat generated depends on two factors—the resistance of the material and the amount of current passing through it. Through the use of special constants, temperature can be converted directly into units of power called *watts*. These

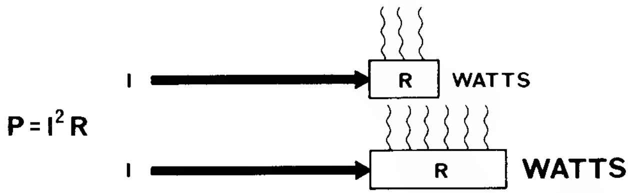


Fig. 4-20. Power dissipated increases as resistance increases.

units can be found by multiplying the resistance by the square of the current. Fig. 4-19 shows how increasing the current increases the heat generated and as a result the power dissipated in the resistor. Fig. 4-20 shows how increasing the size of the resistor (while maintaining the same

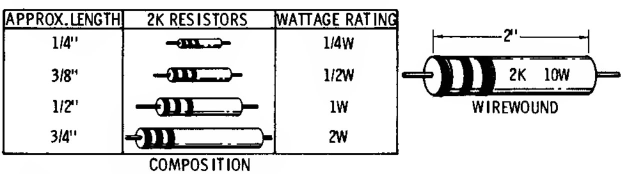


Fig. 4-21. Comparison of resistor size versus wattage rating.

current) increases the power dissipated. Fig. 4-21 shows how resistor size varies with typical wattage ratings. A wirewound resistor is shown for comparison.

Q4-21. Power varies directly as the square of the _____.

Q4-22. Doubling the size of a resistor will __________ the amount of power dissipated by it.

Your Answers Should Be:

A4-21. Power varies directly as the square of the **current**.

A4-22. Doubling the size of a resistor will **double** the amount of power dissipated by it. (This statement is true only if the current is maintained at the same value.)

Effect of Temperature on Resistance

As current passes through a resistor, heat is generated. The heat in turn will cause a change in resistor value. The amount of this change depends on the temperature coefficient of the material. Fig. 4-22 shows a chart of a material whose temperature coefficient is +0.55 percent per degree centigrade. The horizontal axis shows the ambient temperature while the vertical axis shows the factor by which the resistance must be multiplied for a particular temperature.

Consider a 100-ohm resistor at 25 degrees where the multiplication factor is 1.0 and therefore the resistance remains 100 ohms. At a temperature of 120 degrees the multiplication factor is 1.5 and the resistance is 150 ohms. At a temperature of 185 degrees the multiplication factor is 2.0 and the resistance will be 200 ohms. This particular chart shows an increase in resistance with temperature, or a positive temperature coefficient. Some materials exhibit a negative coefficient and can be used to compensate for circuits in which changes in resistance will seriously affect their operation.

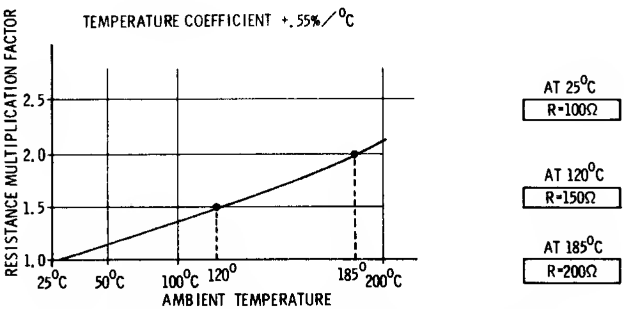


Fig. 4-22. Resistance increases with temperature.

Variable Resistors

Until now we have considered only fixed resistors. However, let us now examine the construction of those components that are made to be manually variable to answer specific circuit needs. Fig. 4-23 shows a sampling of such variable resistors, also called *potentiometers.*

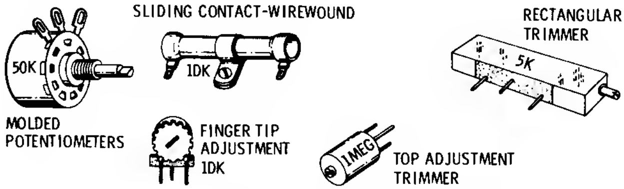
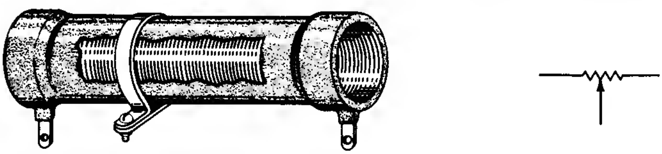


Fig. 4-23. Variable resistors—potentiometers.

Wirewound Sliding Contact—One very common type is the wirewound sliding-contact potentiometer shown in Fig. 4-24. It is constructed in the same fashion as the wirewound fixed resistor discussed previously. The difference lies in the manner in which a portion of the wires is exposed to allow the sliding contact to select any resistance. Once the proper



(*A*) *Construction.* (*B*) *Symbol.*

Fig. 4-24. Sliding contact wirewound potentiometer.

resistance is selected, the screw may be tightened, which will tighten the clamp and prevent a change in the tap position. The schematic symbol for this type of resistor is shown in Fig. 4-24B. Where a high wattage resistor is required the wirewound type will be used.

Q4-23. When a material's resistance decreases as its temperature increases it is said to have a(an) ________ temperature coefficient.

Q4-24. The temperature of a material (*increases, decreases*) as the current through it increases.

Your Answers Should Be:

A4-23. When a material's resistance decreases as its temperature increases it is said to have a **negative** temperature coeffiicent.

A4-24. The temperature of a material **increases** as the current through it increases.

Rectangular Trimmer—One of the latest types of potentiometers is shown in Fig. 4-25. This rectangular trimmer is ideal for mounting on printed-circuit boards. It consists of a screw-driven sliding contact (also called a wiper), which moves along a resistive winding, both ends of which are terminated in contact pins. At the same time that the contact moves along the resistive winding it makes contact with the collector track (usually made out of a precious metal—low resistance). The middle pin on the component is connected to the collector track.

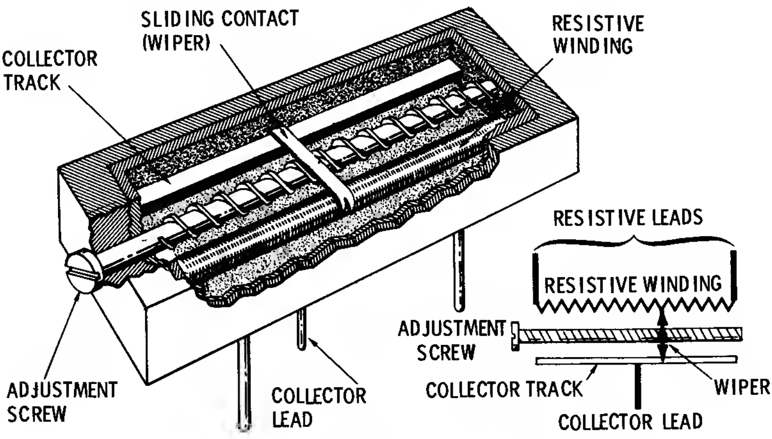


Fig. 4-25. Rectangular trimmer.

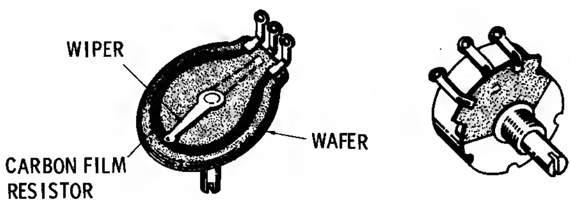


Fig. 4-26. Carbon-composition potentiometer.

Carbon-Composition Potentiometer—One of the most popular of all potentiometers is the carbon-composition type shown in Fig. 4-26. It is used in radio and tv sets for most of the variable controls such as volume, contrast, brightness, and tone. The shaft that connects to the wiper arm is made so that a control knob may be fitted over it. The shaft passes through a threaded section that may fit through a hole in a control panel, and a nut can be screwed on to hold the pot (short for potentiometer) firmly on the panel. With the back of the control removed you can easily see the construction of this component. A carbon-film resistor is bonded to the wafer (an insulating material such as ceramic). The ends of this resistor are connected to the two end contacts of the control. The middle contact is connected to the wiper arm which is formed to provide spring-tension pressure on the film resistor.

These controls cannot be made to carry large currents. Another problem with these controls is that dirt collects inside these units and deposits on the carbon film. This dirt prevents the wiper arm from making a good contact with the resistor and results in erratic operation. Perhaps you have experienced this with your radio. The problem exhibits itself as either noise when the volume control is rotated, or as positions on the volume control where nothing may be heard. This is known as a "noisy" control and can be cured by replacing the old one or cleaning it with a special cleaning compound. For higher-wattage applications a wire-wound resistor may be used in place of the carbon-film resistor.

OHM'S LAW

Basis of the Law

You have already discussed much of the basis for Ohm's law. For example you know that increasing the voltage in a

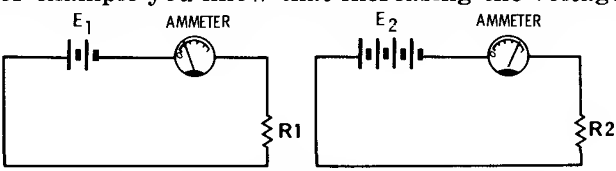


Fig. 4-27. As voltage increases current increases.

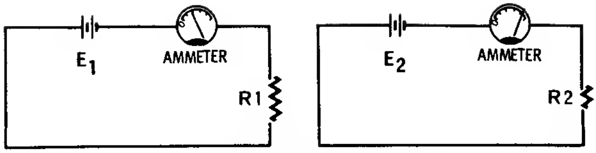


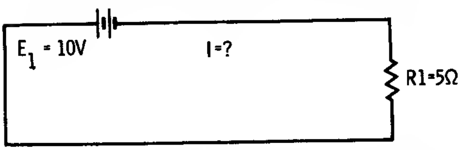
Fig. 4-28. As resistance decreases current increases.

circuit will increase the current. You also know that *decreasing* the resistance in a circuit will increase the *current.* It is very simple to show this relationship as an equation (Fig. 4-29). That is, the current measured in amperes is equal to the voltage measured in volts, divided by the resistance measured in ohms. Using I to represent current, E to represent voltage, and R to represent resistance we have the formula $I = \frac{E}{R}$, which is Ohm's law. Fig. 4-30 shows a sample calculation using this law. Consider a simple series circuit with a voltage of 10 volts applied to a resistor of 5 ohms. How much current is there? Applying Ohm's law we obtain $10V \div 5\Omega = 2A$.

$$\underset{\text{(AMPERES)}}{\text{CURRENT}} = \frac{\overset{\text{(VOLTS)}}{\text{VOLTAGE}}}{\underset{\text{(OHMS)}}{\text{RESISTANCE}}} \qquad I = \frac{E}{R}$$

Fig. 4-29. Ohm's law.

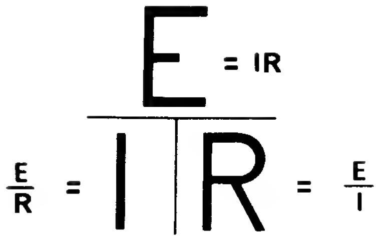
Circuits are not always as straightforward as this one and you may be given any two of these parameters (voltage, current, or resistance). It is important to be able to adjust the formula accordingly. Simple algebraic rules prevail here and if you are familiar with them you will not need the mnemonic device on the next page. It is known as the Ohm's law pie and simplifies the formula.



$$I = \frac{E_1}{R1} = \frac{10\text{VOLTS}}{5\text{OHMS}} = 2\text{AMPS}$$

Fig. 4-30. Sample Ohm's law calculation.

Fig. 4-31. Ohm's law pie.



Manipulation of Ohm's Law

The use of the formula is simplified in Fig. 4-31. Assume a simple circuit where you are given the current required and the voltage supplied, and you wish to calculate the resistance in the circuit. If you cover up the resistance (R) in the pie you are left with E over I, the equation for resistance. In a similar fashion you may cover I to leave E over R as the formula for the current in the circuit, and you may cover E leaving I times R as the equation for the voltage in the circuit.

Manipulation of the Power Formula

You have been introduced to the equation that says power is equal to the product of the resistance and the square of the current. Fig. 4-32 shows how to rearrange the formula to find the power when any two of the parameters are given. This is accomplished by substituting the Ohm's law parameters in the power formula.

$$P = I^2R \quad \text{FOR R SUBSTITUTE } \frac{E}{I}$$

$$P = I^2\left(\frac{E}{I}\right) = IE \quad \text{FOR I SUBSTITUTE } \frac{E}{R}$$

$$P = \left(\frac{E}{R}\right)E = \frac{E^2}{R}$$

Fig. 4-32. Manipulating the power formula.

Q4-25. A 960-watt toaster is plugged into a 120-volt alternating-current outlet (Note that all formulas apply to ac as well as dc). It will draw a current of ________ amperes. The resistance of its heating element is ________ ohms.

Your Answer Should Be:

A4-25. A 960-watt toaster is plugged into a 120-volt a-c outlet. It will draw a current of 8 amperes. The resistance of its heating element is 15 ohms. There are several ways to tackle this one but the most direct is the following:

Since $P = EI$, then $I = P \div E = \frac{960 \text{ watts}}{120 \text{ volts}} = 8$

Then $I = 8$ amperes

From Ohm's law $R = E \div I = \frac{120 \text{ volts}}{8 \text{ amperes}}$
$= 15$ ohms

Use of Ohm's Law Without Basic Units

Until now you have considered the solution of simple series circuit problems using the basic units of volts, ohms, and amperes. Unfortunately, it is more usual in electronics to use units like milliamps (one-thousandth of an ampere) or kilohms (one thousand ohms). Consider the table shown in Fig. 4-33. It lists some of the most often used units and shows how they behave in the Ohm's law formula. Consider the first entry in the table. If ohms and milliamperes are given then the answer will be in millivolts. Note that you may also say that when milliamps and millivolts are given the answer will be in ohms. Although this does not represent all of the combinations it does have those most often encountered in electronics. If you have a facility with the

OHMS Ω	X	AMPERES a	=	VOLTS V
OHMS Ω	X	MILLIAMPERES ma	=	MILLIVOLTS mV
OHMS Ω	X	MICROAMPERES μa	=	MICROVOLTS μV
KILOHMS KΩ	X	AMPERES a	=	KILOVOLTS KV
MEGOHMS MΩ	X	AMPERES a	=	MEGAVOLTS MV
KILOHMS KΩ	X	MILLIAMPERES ma	=	VOLTS V
MEGOHMS MΩ	X	MICROAMPERES μa	=	VOLTS V
MEGOHMS MΩ	X	MILLIAMPERES ma	=	KILOVOLTS KV
KILOHMS KΩ	X	MICROAMPERES μa	=	MILLIVOLTS MV

Fig. 4-33. Table of most often used Ohm's law expressions.

powers of ten you will not need this table, but it might still serve as a quick check on your units.

Fig. 4-34 shows some sample calculations using the table in Fig. 4-33. A current of 30 ma is passed through a 20K resistor. Thus, 20×30 is 600 and, from the table, K ohms $\times$ ma gives us volts. Answer 600 volts. Similarly, $80 \div 4 = 20$, and mv and microamps gives K ohms or 20K. Once again,

$$20K\Omega \text{ X } 30ma = 600 \text{ VOLTS}$$

$$\frac{80mV}{4\mu a} = 20 \text{ KILOHMS}$$

$$\frac{6KV}{2M\Omega} = 3 \text{ MILLIAMPS}$$

Fig. 4-34. More sample calculations using Ohm's law table.

$6 \div 2 = 3$ and Kv $\div$ MΩ is milliamps—3 ma. Note how we use only the K and the M to abbreviate kilohms and Megohms. To gain an even better facility with these units you must practice. See how well you can complete the table below.

Q4-26. In completing this table make sure that your answers are in the required units. That is, if ohms and milliamps are given your answer should be in millivolts rather than in a corresponding quantity of volts.

	RESISTANCE	CURRENT	VOLTAGE
1	500Ω	3a	
2	6000Ω	5ma	
3	4KΩ		20V
4		10ma	120V
5	2MΩ		40V

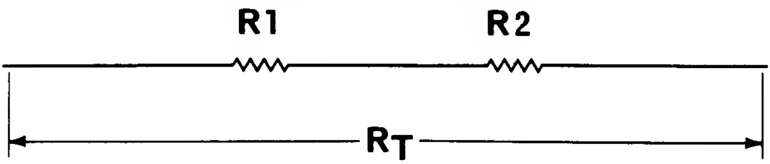
Your Answer Should Be:

A4-26.

	RESISTANCE	CURRENT	VOLTAGE
1	500Ω	3a	1500V
2	6000Ω	5ma	30,000 mV
3	4KΩ	5ma	20V
4	12KΩ	10ma	120V
5	2MΩ	20μa	40V

Resistors in Series

Previously, we have considered only a simple series circuit containing a source of voltage and one resistor. What happens when there is more than one resistor in a circuit? Fig. 4-35 shows two resistors in series (R1 and R2). They



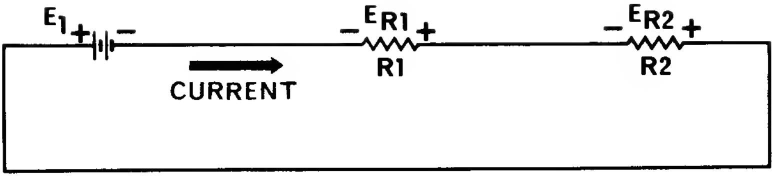
TOTAL (SERIES) RESISTANCE = R_T = R1 + R2

Fig. 4-35. Formula for calculating series resistance.

are in series because the current passing through one must also pass through the other. To find the total resistance (R_T) of this combination it is necessary only to add the two resistors together. Thus a 20-ohm resistor in series with a 30-ohm resistor would give us a total resistance of 50 ohms.

Kirchhoff's First Law

Voltage Drops—How do voltage and current behave in a series circuit containing more than one resistor? For the answer to this we must go to Kirchhoff's first law. Fig. 4-36 shows a simple series circuit containing two resistors in



$E_1 = E_{R1} + E_{R2}$ or

$E_1 + E_{R1} + E_{R2} = 0$

KIRCHHOFF'S FIRST LAW

Fig. 4-36. The algebraic sum of the voltages in a series loop is zero.

series with a source of voltage. First consider the current in the circuit. Since there is only one path for it, the current measured anywhere in the circuit will be the same. Not so with the voltage! When current goes through a resistor there is a voltage developed across the resistor. This voltage is referred to as a *voltage drop*. To understand Kirchhoff's law we must consider the polarities of the voltage drops in a circuit.

You are already familiar with the polarity at the terminals of a battery as they are shown. What of the polarity of the voltage drops across the resistors? A simple rule prevails. The side of a resistor at which the *current enters* is considered *negative*. Thus if the voltage at the battery (E_1) is considered to be positive, then the voltage across the resistors (E_{R1} and E_{R2}) must be negative. Since we cannot drop any more voltage in a circuit than that which is supplied, the sum of the voltage drops in the circuit must equal the source voltage, that is, $E_1 = E_{R1} + E_{R2}$. Another way of saying this is that the algebraic sum (the sum considering the polarities of the voltages) of the voltages in a series circuit is zero. This is Kirchhoff's first law. It may be written as $E_1 + E_{R1} + E_{R2} = 0$. Note that this holds true no matter how many components there are in the circuit.

Q4-27. Three resistors in series have values of 12K, 18K and 22K. The total resistance is ________.

Q4-28. Two resistors in series with values of 1 Meg and 6.8K give us a total resistance of ________.

Q4-29. The expression for Kirchhoff's law with three series resistors is ________.

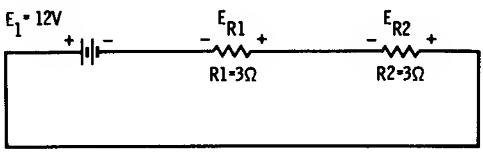
Your Answers Should Be:

A4-27. Three resistors in series have values of 12K, 18K, and 22K. The total resistance is 52K.

A4-28. Two resistors in series with values of 1 Meg and 6.8K give us a total resistance of **1006.8K.** This one is a little tricky. To add the resistors they must be in the same units. For example converting both units to ohms you get 1 Meg (1,000,000 ohms) plus 6.8K (6800 ohms) or 1,006,800 ohms. Or, converting the 1 Meg to 1000K you get 1006.8K.

A4-29. The expression for Kirchhoff's law with three series resistors is $\mathbf{E_1 + E_{R1} + E_{R2} + E_{R3} = 0}$.

Application—Fig. 4-37 shows a sample calculation applying Ohm's and Kirchhoff's laws. Two equal resistors are shown in series with a 12-volt battery. We wish to find the current in the circuit and the voltage dropped across each of the components. To begin, we know that the current in the circuit is equal to the voltage divided by the total resistance. Therefore, it is necessary to find the total resistance. As per step 1, $R_T = 6$ ohms. Then, in step 2 we may calculate the current to be 2 amperes. To calculate the voltage drops



STEP:

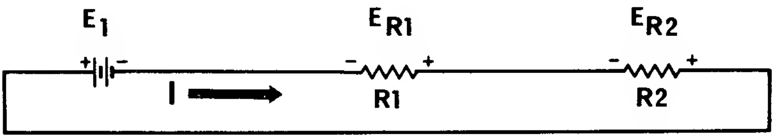
1. $R_T = R1 + R2 = 3\Omega + 3\Omega = 6\Omega$
2. $I = \dfrac{E_1}{R_T} = \dfrac{12V}{6\Omega} = 2a$
3. $E_{R1} = I_{R1} \times R1 = 2a \times 3\Omega = 6V$
4. $E_{R2} = I_{R2} \times R2 = 2A \times 3\Omega = 6V$
5. $E_1 = E_{R1} + E_{R2} = 12V = 6V + 6V$

Fig. 4-37. Sample calculation—circuit with two equal series resistors.

we must consider the current through each resistor and its resistance. The current through resistor R1 is called I_{R1}. The voltage across it is calculated as 6 volts in step 3. Step 4 calculates the voltage across R2 as 6 volts also.

This proves something that should be obvious. That is, that two equal resistors in a series circuit will have the same voltage drops. This is due to the fact that the current through them is equal because of the series nature of the circuit. Step 5 shows that Kirchhoff's first law has been satisfied; that is, the sum of the voltages in the circuit must equal the source voltage. Note again that circuits like these can be solved no matter how many components are placed in series. The system will be the same. In the problems below try to find the simplest approach to the solutions.

Q4-30. Complete the table below.



	E_1	I	R1	R2	R_T	E_{R1}	E_{R2}
1	12V		4Ω	2Ω			
2	36V	3a		4Ω			
3			12Ω	8Ω			16V
4	100V	5a				60V	
5		20a	100Ω	200Ω			

Q4-31. Calculate the total power dissipated and power dissipated across each resistor in problem 3 of Q4-30.

Your Answers Should Be:

A4-30.

	E_1	I	R1	R2	R_T	E_{R1}	E_{R2}
1	12V	2a	4Ω	2Ω	6Ω	8V	4V
2	36V	3a	8Ω	4Ω	12Ω	24V	12V
3	40V	2a	12Ω	8Ω	20Ω	24V	16V
4	100V	5a	12Ω	8Ω	20Ω	60V	40V
5	6KV	20a	100Ω	200Ω	300Ω	2KV	4KV

Let us examine some of the techniques applied to solve these problems. In problem 1 you find the total resistance, then the current, and finally the voltage across each of the components. In problem 2 the total resistance can be found from the voltage and current. Then the resistance of R1 can be found as well as the voltage drop across each of the components. In problem 3 the key is finding the current in the circuit by using the resistance of R2 and voltage drop across it. Then the voltage drop across R1 may be calculated and thence the total voltage.

In problem 4 the total resistance can be calculated from the applied voltage and current. The voltage drop across R1 and the current may be used to calculate the resistance of R1. The value of R2 may now be found. Using Kirchhoff's law, the value of E_{R2} could have been found immediately. In problem 5 you may find total resistance and, using the current, you may find E_1, E_{R1}, and E_{R2}.

A4-31. Using P = EI we have:

$P_{RT} = E_1 \times I = 40V \times 2A = 80W$

$P_{R1} = E_{R1} \times I = 24V \times 2A = 48W$

$P_{R2} = E_{R2} \times I = 16V \times 2A = 32W$

Notice here that the sum of the power dissipated across each of the resistors is equal to the power applied. This is always true.

Resistors in Parallel

Kirchhoff's Second Law—Now we will consider what happens in a circuit where there is more than one path for current to follow. Such a circuit is called a parallel circuit and it is illustrated in Fig. 4-38. Two resistors are shown connected so that the current will leave the battery and split up at the junction and then pass through each of the resistors. Kirchhoff's second law describes the manner in which

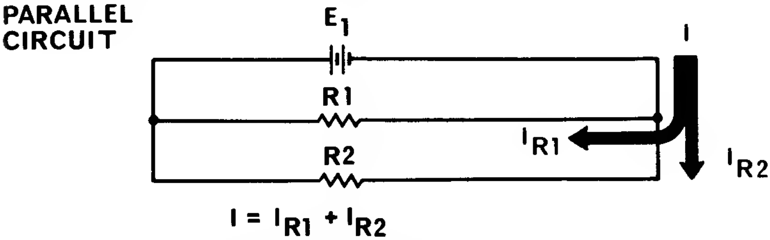
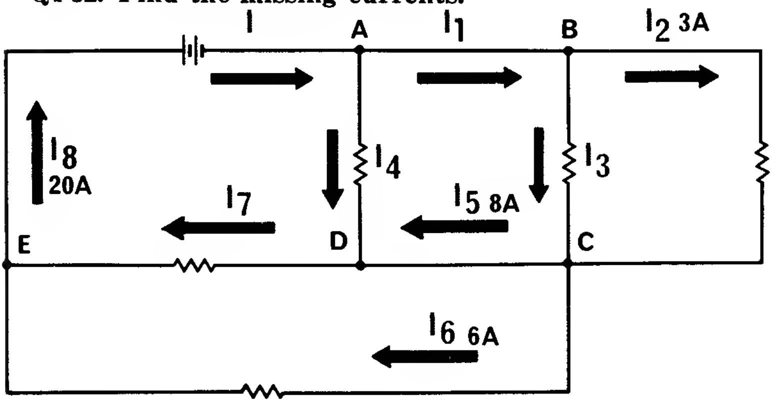


Fig. 4-38. The sum of the current entering a junction equals the sum of the current leaving a junction.

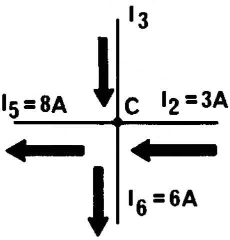
the current divides. It is very logical and can be readily understood. The sum of the current entering a junction must equal the sum of the current leaving a junction. The equation is shown in the figure. For example, if a current of 5 amperes enters the junction and R1 draws 3 amperes then R2 must draw 2 amperes. Which of these resistors do you suppose has the lowest resistance? It stands to reason that the resistor drawing most current has the least resistance.

Q4-32. Find the missing currents.



Your Answer Should Be:

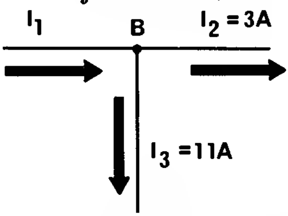
A4-32. **I = 20 amps, I_1 = 14 amps, I_3 = 11 amps, I_4 = 6 amps, I_7 = 14 amps.** The methods used are described below. Examine the illustration until you find a junction where there is only one unknown current; for example, junction C.



CURRENT INTO JUNCTION		CURRENT LEAVING JUNCTION
$I_3 + I_2$	=	$I_5 + I_6$
$I_3 + 3A$	=	$8A + 6A$

$$I_3 = 11A$$

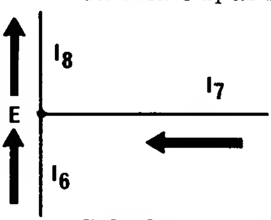
I_3 may be calculated as shown. Now consider junction B.



$$I_1 = I_2 + I_3$$

$$I_1 = 3A + 11A = 14A$$

Calculate I_1 as shown. Now junction E.

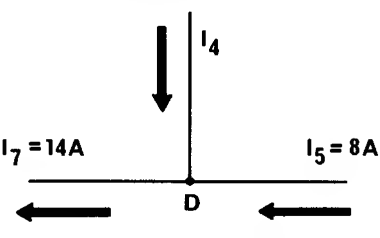


$$I_8 = I_6 + I_7$$

$$20A = 6A + I_7$$

$$I_7 = 14A$$

Calculate I_7 as shown. Junction D.



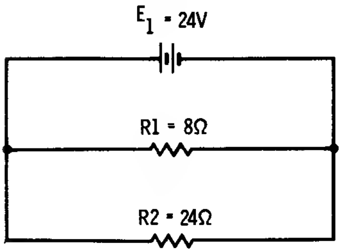
$$I_7 = I_4 + I_5$$

$$14A = I_4 + 8A$$

$$I_4 = 6A$$

Calculate I_4. By inspection $I = I_8 = 20$ amps.

Two-Path Parallel Circuit—Fig. 4-39 shows a sample Ohm's law/Kirchhoff's law calculation for a simple parallel circuit. Step 1 shows a sample observation that the applied voltage is the same as the voltage dropped across each of the resistors. Step 2 uses simple Ohm's law to calculate the current through R1. Step 3 does the same for R2. Step 4 applies Kirchhoff's law to find the total current. Using the total current in Step 5 the total resistance is calculated.



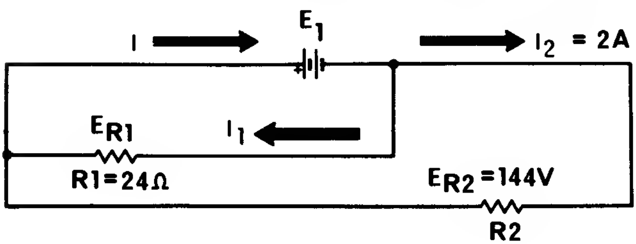
STEP:

1. $E_1 = E_{R1} = E_{R2}$ (OBSERVATION)
2. $I_{R1} = \frac{E_{R1}}{R1} = \frac{24\,V}{8\Omega} = 3a$
3. $I_{R2} = \frac{E_{R2}}{R2} = \frac{24V}{24\Omega} = 1a$
4. $I = I_{R1} + I_{R2} = 3a + 1a = 4a$
5. $R_T = \frac{E_1}{I} = \frac{24V}{4a} = 6\Omega$

Fig. 4-39. Sample parallel circuit calculation.

Note that the resistance found in this manner is less than either of the resistors in the circuit. A logical explanation of this can be found if we use our highway analogy once more. Consider a superhighway (a low resistance path for cars) that is paralleled by an old dirt road (a high resistance path for cars). Even though very little traffic will travel the dirt road a few cars will be drained from the super highway thereby serving to reduce the resistance of the system below that of the highway alone. In the same fashion the parallel resistance of the circuit will always be less than the smallest resistor in the parallel system.

Q4-33. Calculate the missing values in the illustration.



$R_T =$

Your Answer Should Be:

A4-33. Check your method against the illustration below.

STEP:

1. $R2 = \dfrac{E_{R2}}{I_2} = \dfrac{144V}{2A} = 72\,\Omega$

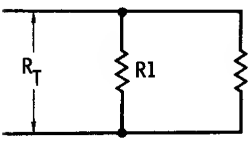
2. $E_1 = E_{R1} = E_{R2} = 144V$

3. $I_1 = \dfrac{E_{R1}}{R1} = \dfrac{144V}{12\,\Omega} = 6A$

4. $I = I_1 + I_2 = 6A + 2A = 8A$

5. $R_T = \dfrac{E_1}{I} = \dfrac{144V}{8A} = 18\,\Omega$

Total Parallel Resistance Calculation—Fig. 4-40 shows the method for calculating the total resistance of two resistors in parallel. The first method shows that the reciprocal

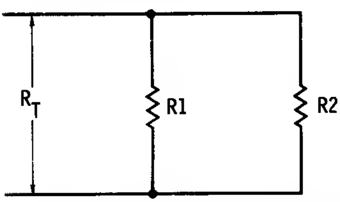


$$\frac{1}{R_T} = \frac{1}{R1} + \frac{1}{R2}$$

$$R_T = \frac{R1\,R2}{R1 + R2}$$

Fig. 4-40. Formula for calculating parallel resistance.

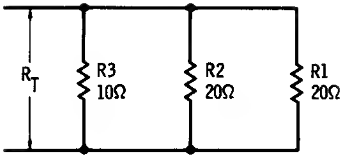
of the total resistance is equal to the sum of the reciprocals of each individual resistance. This formula holds true no matter how many resistors are placed in parallel. The other formula shown is a special formula used to handle only two resistors. Here the total resistance is equal to the product of the resistors divided by the sum of the resistors.



$R1 = R2$

$$R_T = \frac{R1\,R1}{R1 + R1} = \frac{R1^2}{2R1} = \boxed{\frac{R1}{2}}$$

Fig. 4-41. Calculating resistance for two equal parallel resistors.



STEP:

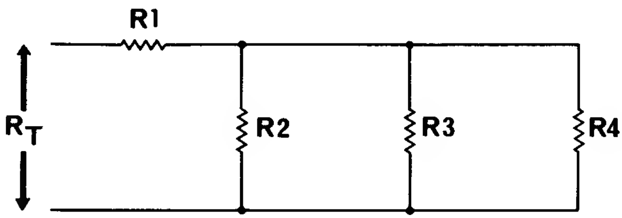
1. $R1 = R2 \therefore R_{R1 + R2} = \frac{R1}{2} = \frac{20}{2} = 10\Omega$

2. $R3 = R_{R1 + R2}$

3. $R_T = \frac{R3}{2} = \frac{10}{2} = 5\Omega$

Fig. 4-42. Sample calculation—three resistors in parallel.

Fig. 4-41 shows a special case where the resistors in parallel are equal. By substituting in the equation you find that the total resistance is equivalent to half the value of one of the resistors. If you work out the equation for any number of *parallel equal* resistors you will find that the total resistance will equal the value of one resistor divided by the number of resistors in parallel. A sample calculation is shown in Fig. 4-42. Noting that R1 = R2 we see that value of $R_{R1 + R2} = \frac{R1}{2} = \frac{20}{2} = 10$ ohms. Since this is the same value of resistance as R3, then $R_T = \frac{R3}{2} = \frac{10}{2} = 5$ ohms. Using the following illustration, try calculating the resistances that are missing.



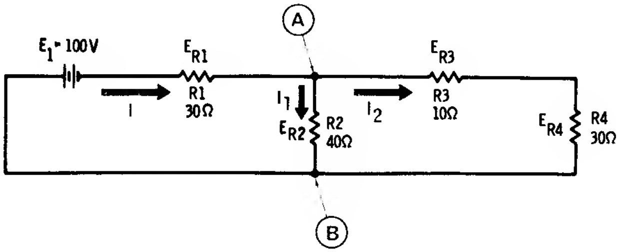
Q4-34. Complete the table below.

	R_T	R1	R2	R3	R4
1		6.8K	33K	33K	33K
2	50K		180K	90K	180K
3	100K		20K	0	20K
4		500Ω	300K	100K	75K
5		4Ω	48Ω	8Ω	48Ω

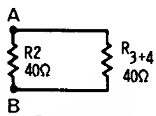
Your Answer Should Be:

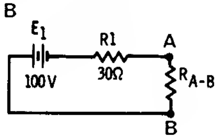
A4-34.

	R_T	R1	R2	R3	R4
1	17.8K	6.8K	33K	33K	33K
2	50K	5K	180K	90K	180K
3	100K	100K	20K	0	20K
4	38K	500Ω	300K	100K	75K
5	10Ω	4Ω	48Ω	8Ω	48Ω



STEP:





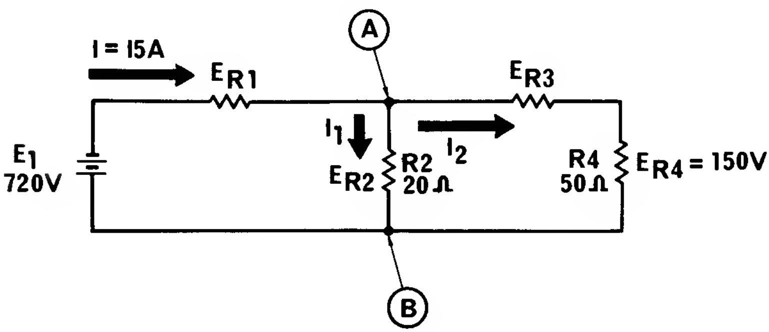
1. $R3 + R4 = 10 + 30 = 40$ OHMS
2. SINCE $R2 = R_{3+4}$, $R_{A-B} = \frac{R2}{2} = \frac{40}{2} = 20$ OHMS
3. $R_T = R1 + R_{A-B} = 50 = 30 + 20 = 50$ OHMS
4. $I = \frac{E_1}{R_T} = \frac{100}{50} = 2$ AMPS
5. $E_{R1} = IR1 = 2 \times 30 = 60$ VOLTS
6. $E_{RA-B} = E_1 - E_{R1} = 100 - 60 = 40$ VOLTS
7. $I_{R2} = I_1 = \frac{E_{R2}}{R2} = \frac{40}{40} = 1$ AMP
8. $I_2 = I - I_1 = 2 - 1 = 1$ AMP
9. $E_{R3} = I_2 R3 = 1 \times 10 = 10$
10. $E_{R4} = I_2 R4 = 1 \times 30 = 30$ VOLTS

Fig. 4-43. Sample calculation—series-parallel circuit.

Series-Parallel Circuit Calculations—Fig. 4-43 shows a sample calculation for a simple series-parallel circuit. Consider the steps that lead to its solution. First, the series resistance of R3 and R4 is found. Noting that this resistance is the same as R2, the resistance from A to B can be found.

This resistance plus R1 give us the total resistance in the circuit. In step 4 we find the current leaving E_1. Since all of this current passes through R1 we find E_{R1}. Applying Kirchhoff's first law we note that the difference between E_1 and E_{R1} is E_{R2}. Applying Ohm's law we find the current through R2 to be E_{R2} divided by R2. Applying Kirchhoff's second law we find that the current through R3 and R4 is the difference between I and I_1. Then, applying Ohm's law we find the voltage dropped across R3 and R4.

Now try your luck with a similar problem. The following illustration contains the same circuit used in the sample calculation. You are to solve the problems in the order listed below.



Q4-35. The value of I_2 is __________.

Q4-36. The value of I_1 is __________.

Q4-37. The value of E_{R2} __________.

Q4-38. The value of E_{R3} is __________.

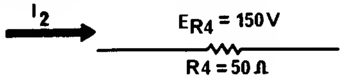
Q4-39. The value of E_{R1} is __________.

Q4-40. The value of R1 is __________.

Your Answers Should Be:

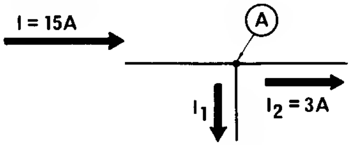
For each of the answers the method is shown in an associated figure.

A4-35. The value of I_2 is **3 amperes.**



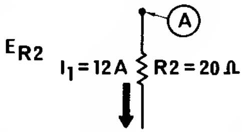
$$I_2 = \frac{E_{R4}}{R4} = \frac{150}{50} = 3 \text{ AMPS}$$

A4-36. The value of I_1 is **12 amperes.**



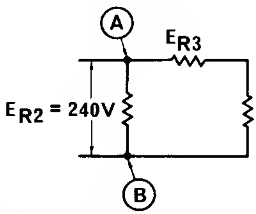
$$I_1 = I - I_2 = 15 - 3 = 12 \text{ AMPS}$$

A4-37. The value of E_{R2} is **240 volts.**



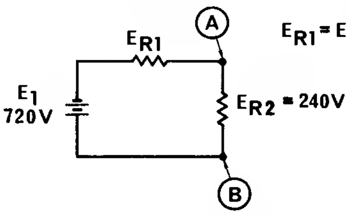
$$E_{R2} = I_1\,R2 = 12 \times 20 = 240 \text{ VOLTS}$$

A4-38. The value of E_{R3} is **90 volts.**



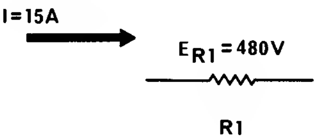
$$E_{R3} = E_{R2} - E_{R4} = 240 - 150 = 90 \text{ VOLTS}$$

A4-39. The value of E_{R1} is **480 volts.**



$$E_{R1} = E_1 - E_{R2} = 720 - 240 = 480 \text{ VOLTS}$$

A4-40. The value of R1 is **32 ohms.**



$$R1 = \frac{E_{R1}}{I} = \frac{480}{15} = 32 \text{ OHMS}$$

Front-to-Back Resistance of a Diode

Fig. 4-44 illustrates the fact that a resistor is a bilateral device. That is, it offers the same resistance to current no matter which direction the current passes through it. A semiconductor diode is a unilateral device. It is constructed

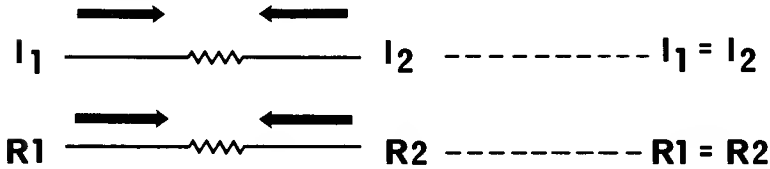


Fig. 4-44. A resistor is a bilateral device.

of materials like germanium and silicon and will be discussed in great detail in the next chapter. Here, however, we will consider only the nature of its resistance. Fig. 4-45 shows how the resistance of the diode depends on the direction of the current. Note how the current passes readily from left to right through this component while almost no

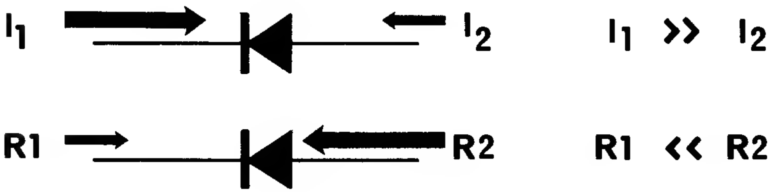


Fig. 4-45. A semiconductor diode is a unilateral device.

current passes from right to left. In a good diode the ratio of the resistance in one direction to the resistance in the other direction (known as front-to-back ratio) may be as high as 100,000 to 1.

Current and Voltage Relationship in a Circuit

When an alternating current is applied to a resistor (Fig. 4-46) the waveforms representing the applied voltage, the current, and the voltage across the resistor are similar. However, when an alternating current is applied to a diode

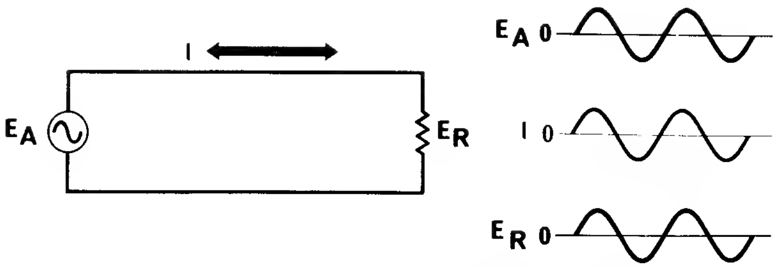


Fig. 4-46. Alternating current applied to a resistor.

(Fig. 4-47) you will find that although the applied voltage and the voltage across the diode are similar, the current is much different. Fig. 4-47 shows how during the positive half-cycle the diode offers little resistance and allows a cur-

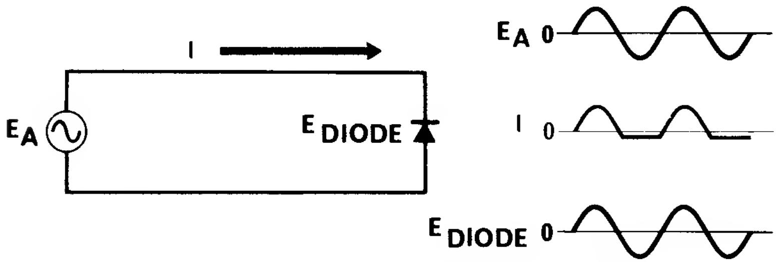


Fig. 4-47. Alternating current applied to a diode.

rent. During the negative half-cycle the diode offers a maximum resistance and there is very little current. Later you will see how this unilateral property of the diode can be put to good use in many circuit applications.

SUMMARY QUESTIONS

1. A simple circuit is composed of a source of voltage, an object to do work on, and a method of delivering the electrical energy.
   a. The object that the work is done on is called the ____.
   b. There is no current in a circuit when a switch is ____.
2. Resistance is the opposition offered to the current in a circuit. It is measured in units called ohms.
   a. When there is a current of 1 ampere through a resistance of 1 ohm the voltage applied is ________ volt(s).

b. A variable resistor is called a(an) ________.
c. The value of a resistor whose colors are brown, gray, and green is ________.
d. As current increases power ________.

3. The relationship between resistance, current, and voltage in a circuit is regulated by Ohm's law.
   a. Ohm's law is stated as the current in a circuit is equal to the ________ divided by the ________.
   b. The total resistance in a series circuit is equal to the ________ of the individual resistors.
   c. The sum of the voltages in a series loop is equal to the ________.
   d. The total resistance of four 140K resistors in parallel is ________.
   e. The sum of the current entering a junction is equal to the ________ of the currents ________ the junction.
   f. The voltage across two unequal parallel resistors is ________.
4. Semiconductor diodes allow current readily in one direction.
   a. The reason for this is that they have a high ________ resistance ratio.
   b. When alternating current is applied to a diode there is ________ current for half of each cycle.

SUMMARY ANSWERS

1a. The object that the work is done on is the **load.**
1b. There is no current in a circuit when a switch is **open.**
2a. When a current of 1 ampere flows through a resistance of 1 ohm the voltage applied is 1 volt.
2b. A variable resistor is called a **potentiometer.**
2c. The value of a resistor whose colors are brown, gray, and green is **1.8 Meg.**
2d. As current increases, power **increases.**
3a. Ohm's law is stated as the current in a circuit is equal to the **voltage** divided by the **resistance.**
3b. The total resistance in a series circuit is equal to the **sum** of the individual resistors.
3c. The sum of the voltages in a series loop is equal to the **applied voltage.** (If "algebraic sum" then equal to zero.)
3d. The total resistance of four 140K resistors in parallel is **35K.**
3e. The sum of the current entering a junction is equal to the **sum** of the currents **leaving** the junction.
3f. The voltage across two unequal parallel resistors is the **same.**
4a. The reason for this is that they have a high **front-to-back** resistance ratio.
4b. When alternating current is applied to a diode there is **almost no** current for half of each cycle.

5

Semiconductor Principles

What You Will Learn

In this chapter you are going to learn another way to tell the difference among insulators, conductors, and semiconductors. You will also study the molecular structure of some of the most widely used semiconductors. Then, you will find out how natural semiconductors can be made to operate more efficiently. Finally, you are going to study some practical applications of semiconductors.

In a previous chapter you learned how to distinguish among conductors, semiconductors, and insulators. Briefly, this distinction was a matter of the current-carrying capabilities. In this chapter, however, you will find that there is another way to distinguish among them—by energy levels. Actually, energy levels account for the difference in current-carrying capacities.

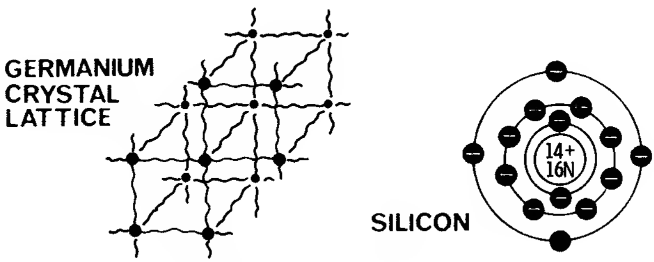


Fig. 5-1. Molecular structures.

ATOMIC STRUCTURE

We know from Chapter 2 that electrons orbit the atom's nucleus in so-called shells. We also know that these shells have fixed numbers of electrons in them. That is, the first shell always has two electrons; the second, always eight. The third shell may have eighteen or eight (depending on the element) and so on. If we can't see an atom, how do scientists know this to be true?

Energy Levels

Scientific experiments show that the electron must have a certain quantity of energy to exist in a stable orbit in a given shell. This quantity is called the electron's *energy level.* Scientists also know that the energy level occurs in discrete amounts. In Fig. 5-2 the first electron has an energy

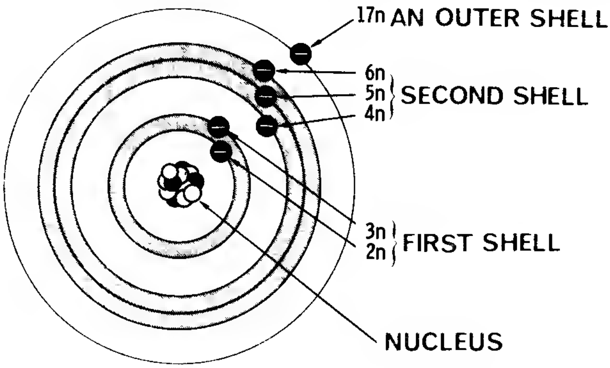


Fig. 5-2. Energy levels in electron shells.

level equal to 2n. The next outer electron has an energy level equal to 3n; the next outer electron has an energy level equal to 4n, and so forth. But, *no* electron has an energy level of, say, 2.5n or 3.5n. Energy levels always differ by whole integers. This is why scientists can so accurately describe the atom's electron structure.

They know for instance, that electrons with energy levels of 2n and 3n always occupy the first shell. Electrons with energy levels of 4n, 5n, and 6n will always occupy the second shell. An electron having an energy level of 17n would occupy a shell quite a distance from the nucleus.

Energy Bands

One of the interesting phenomena which scientists have observed is that energy levels of electrons group themselves into bands when individual atoms are combined into crystals. Valence electrons (those in the outermost shell) have energies that fall in the valence band. Above this is a *forbidden band* (or *energy gap*) and then the *conduction* band. The width of the forbidden band varies with the nature of the material; insulators have wide energy gaps, semiconductors have small gaps, and conductors have conduction and valence bands that overlap.

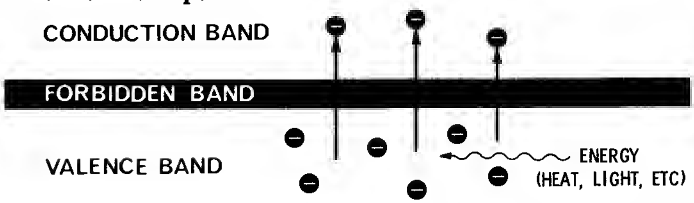


Fig. 5-3. Energy bands.

The concept of energy bands is particularly important in understanding the operation of semiconductors. An electron can exist in either the valence or the conduction band. All that is needed is the addition of the necessary energy to carry it through the forbidden band. For example, an electron in the lower band may suddenly acquire energy from external heat or radiation. It will then appear in the conduction band where it can be used for electric current.

Q5-1. Another method for distinguishing among conductors, insulators, and semiconductors is by ________ ________.

Q5-2. To exist in any shell a(an) ________ must have a certain quantity of energy.

Q5-3. Energy levels always differ by ________ integers.

Q5-4. The energy level that doesn't exist is the ________ band.

Q5-5. Energy levels group together as energy ________.

Q5-6. These energy bands are called ________, ________, and ________.

Your Answers Should Be:

A5-1. Another method for distinguishing among conductors, insulators, and semiconductors is by **energy levels.**

A5-2. To exist in any shell an **electron** must have a certain quantity of energy.

A5-3. Energy levels always differ by **whole** integers.

A5-4. The energy level that doesn't exist is the **forbidden** band.

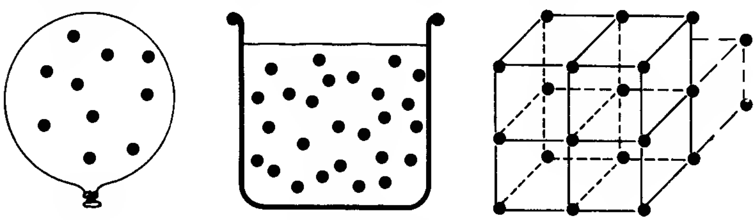
A5-5. Energy levels group together as energy **bands.**

A5-6. These energy bands are called **valence, conduction,** and **forbidden (or energy gap).**

CRYSTALLINE STRUCTURE

Properties of Crystals

As you know, matter can exist in any of three states: solid, liquid, or gas. In the gas state the atoms or molecules are spread far apart and haphazardly arranged (Fig. 5-4A). In the liquid state they are packed closer together but still arranged haphazardly (Fig. 5-4B). In the solid state they take on an orderly geometric pattern in three dimensions (Fig. 5-4C). This pattern is known as a *crystal lattice.* Atoms are arranged in seven crystal-lattice systems. Semiconductors fall under the *cubic* lattice system.



(*A*) *Gas state.* (*B*) *Liquid state.* (*C*) *Solid state.*

Fig. 5-4. Arrangement of atoms in matter.

Definition—A crystal is any solid whose atoms or molecules are arranged in a three-dimensional geometrical pattern. This pattern is called a *lattice* and is composed of single crystal lattice cells.

Unit Cell—A unit cell is the smallest geometrical solid from which the crystal lattice can be generated. It is often quite different from and smaller than the single crystal lattice cell. The geometrical solid is generated by using the smallest number of atoms or molecules.

Face-Centered Cube—A crystal lattice comprises many identical lattice cells going off in three dimensions and held together by atomic binding forces. One such cell is the face-centered cube shown in Fig. 5-5. Each cube face has an atom (A) which is surrounded by 12 other atoms. Copper forms this type of lattice.

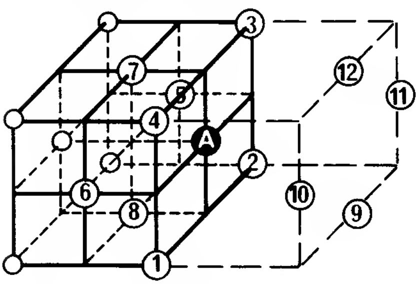


Fig. 5-5. Face-centered cube.

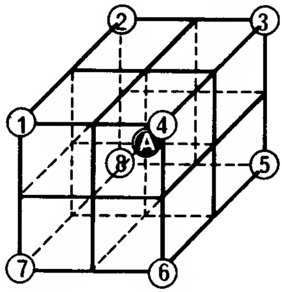


Fig. 5-6. Body-centered cube.

Body-Centered Cube—The body-centered cube contains a single centered atom and is surrounded by eight other atoms (Fig. 5-6). In this case, atom A is less completely surrounded than atom A of the face-centered cube. Silicon and germanium form this type of cubic crystal lattice.

Q5-7. Atoms in gases and liquids are arranged haphazardly, but in solids they are arranged in ________ ________ ________.

Q5-8. In a face-centered cube each face atom is surrounded by ________ atoms.

Q5-9. In a body-centered cube each center atom is surrounded by ________ atoms.

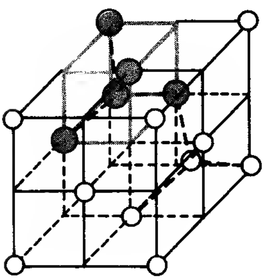
Your Answers Should Be:

A5-7. Atoms in gases and liquids are arranged haphazardly, but in solids they are arranged in **orderly geometric patterns.**

A5-8. In a face-centered cube each face atom is surrounded by 12 atoms.

A5-9. In a body-centered cube each center atom is surrounded by 8 atoms.

Diatomic Crystal Structure—Further investigation of a semiconductor face-centered cube shows that each atom is associated with four other atoms (Fig. 5-7). Each lattice cell is divided into eight unit cells. By examining the darkened unit cell shown you can see that it contains *two atoms;* that is, it is diatomic. From the diatomic unit cells the entire crystal lattice is formed. This particular lattice represents silicon.



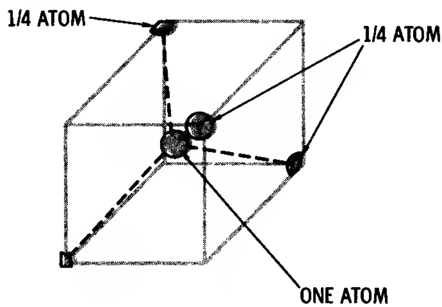


Fig. 5-7. Diatomic crystal structure.

Electrical Characteristics of Crystals

Crystal lattices are held together by electrical binding forces. These forces occur between atoms, molecules, ions, or electrons. Remember that all solids (conductors, semiconductors, and insulators) form into crystals.

Crystal Space Lattice—The crystal lattices you have studied fall under the cubic or regular crystal lattice system. In this space-lattice system the three axes are mutually perpendicular and equal in length and have five points (atoms, ions, or molecules). Other space-lattice systems have their

axes at other angles and different lengths, and may have 2, 3, 4, 5, or 7 points involved. Semiconductors and some metals fall under the cubic system. The rest of the metals and all insulators fall under the space-lattice system.

Covalent Lattices—In many crystals, atoms combine with atoms to form the lattice (Fig. 5-8). When two adjacent atoms share an electron, a *covalent bond* is formed. For instance, the silicon atom has four outer shell electrons and shares these with four neighboring silicon atoms. The covalent bond tends to draw the silicon atoms together while the

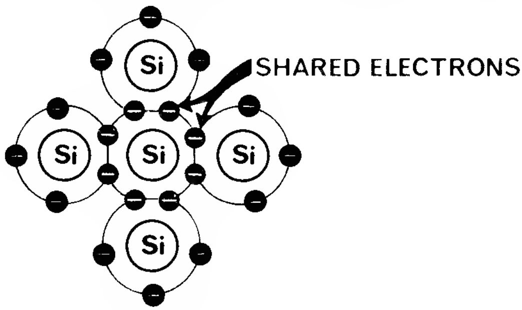


Fig. 5-8. Covalent lattice.

nuclei, being positively charged, tend to repel each other. The forces are balanced to form the crystal lattice and the entire crystal is electrically neutral. Occasionally, a shared electron gains enough energy to free itself and it drifts through the crystal. This kind of covalent lattice binding is typical of semiconductors.

Q5-10. Crystal lattices are held together by electrical binding forces between __________, __________, __________, or __________.

Q5-11. The cubic lattice system is identified by its mutually __________ axes which are __________ in length and have __________ points.

Q5-12. Covalent lattices are held together by __________ which means that two atoms __________ a single __________.

Your Answers Should Be:

A5-10. Crystal lattices are held together by electrical binding forces between **atoms, ions, molecules,** or **electrons.**

A5-11. The cubic lattice system is identified by its mutually **perpendicular** axes which are **equal** in length and have **five** points.

A5-12. Covalent lattices are held together by covalent bonds which means that two atoms **share** a single **electron.**

Ionic Lattices—Ions are atoms which have gained or lost electrons. In such a state they are no longer neutral. The common salt (sodium chloride) crystal is made up of such ions. Each sodium (Na) atom gives up its outer electron to a chlorine (Cl) atom. The sodium ions ($Na+$) become positively charged and tend to repel each other. The chlorine ions ($Cl-$) become negatively charged and tend to repel each other. But the sodium and chlorine ions are oppositely charged and are drawn to each other. With the ionic forces balanced, the result is the crystal lattice shown in Fig. 5-9. Each sodium ion is surrounded by chlorine ions and vice versa. Because the chlorine ions take on an electron, no free electrons exist in the crystal, hence it is an insulator. This kind of ionic-lattice binding is typical of insulators.

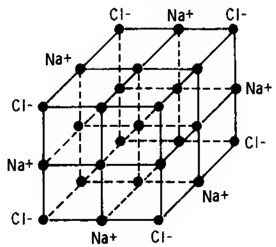


Fig. 5-9. Ionic lattice.

Metallic Crystals—When a large quantity of metallic atoms group together, as in a crystal, their valence (outer shell) electrons can travel about randomly in the metal (Fig. 5-10). These random electrons form an electron cloud around the metal atoms. The cloud, which is negatively charged, surrounds the metal ions (because they have given

up an electron and are positively charged) and acts as a cement to hold the crystal lattice structure together. When the electron cloud forms, the tendency to conduct electrons increases. All metallic crystals, in which this electron cloud binding is typical, are good conductors.

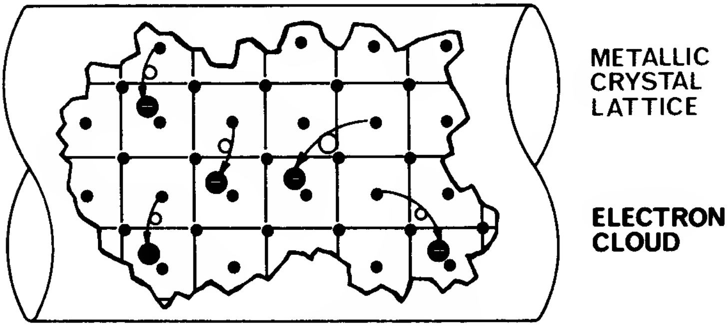
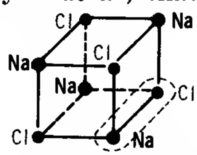


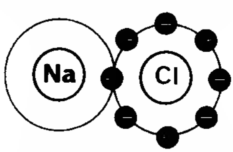
Fig. 5-10. Metallic crystal.

Molecular Lattices—The unit points in the crystal lattices of compounds are atoms and not molecules. In all these solid compounds, atoms of one element do not merge with atoms of the other element. Instead, these elements are arranged in the space lattice to comprise a molecule (Fig. 5-11). Only in the vapor state do the elements actually merge, as shown with salt.

Crystalline Electric Field—The crystal electric field is actually an electrostatic field inside the crystal that holds it together. Ions, covalent bonds, or electron clouds are responsible for it. Remember that the overall crystal is electrically neutral; that is, neither positive nor negative.



(*A*) *Solid molecule.*



(*B*) *Vapor molecule.*

Fig. 5-11. Molecular lattice.

Q5-13. Ionic lattices have ________ free electrons.

Q5-14. Metallic crystals are held together by ________ ________.

Your Answers Should Be:

A5-13. Ionic lattices have **no** free electrons.

A5-14. Metal crystals are held together by **electron clouds.**

TYPES OF SEMICONDUCTOR MATERIALS

Germanium

Germanium is one of the most frequently used semiconductor materials. It has an atomic weight of 73 and its outer ring contains four valence electrons. In its pure state germanium forms a single crystal structure. This means its crystal lattice is uniform and not varied as in polycrystalline materials which may have several crystal lattice systems.

Lattice Structure—The cubic lattice structure shown in Fig. 5-12 is the typical body-centered lattice cell with a diatomic unit cell. Each center germanium atom is associated with four surrounding atoms. The atoms are held together by covalent bonds and the crystal is at best only a fair conductor. Many millions of identical unit cells form the germanium crystal.

Conductivity—Because every atom in the crystal is bonded to four others, the electrons are not free to move

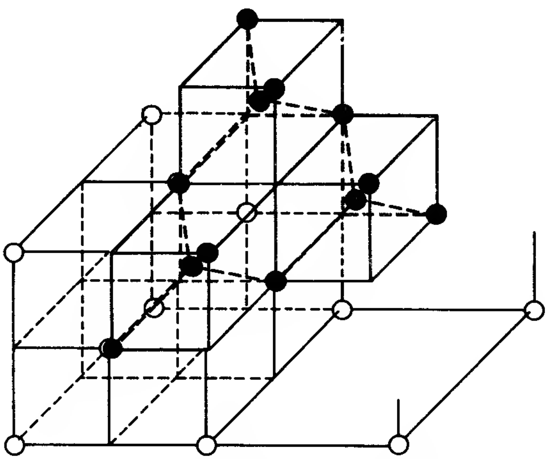


Fig. 5-12. Cubic lattice structure.

about in the crystal. This produces an electrically neutral substance. The entire crystal conducts poorly; only high electrical pressure or high thermal energy will cause a few electrons to move.

Silicon

Silicon is used as often as germanium for electronic purposes. It has an atomic weight of 14 and, like germanium, has four valence electrons. In its pure state, silicon has a single crystal structure. Its space lattice is identical with that of germanium while its conductivity slightly exceeds that of germanium.

Carbon

Fig. 5-13 shows several atoms of carbon. This element is tetravalent; that is, it has four valence electrons. It, too, has a uniform crystal structure like that of germanium and silicon.

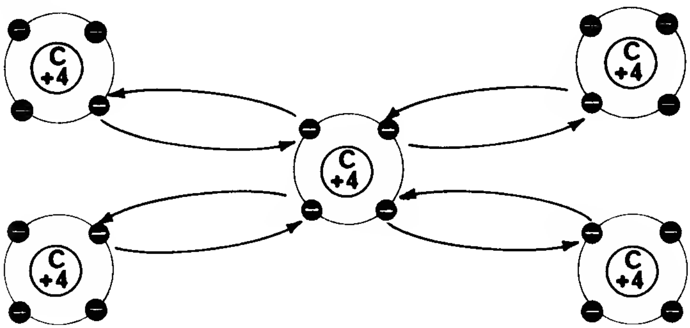


Fig. 5-13. Carbon lattice.

Q5-15. Germanium and silicon have a ________ crystal structure.

Q5-16. Both germanium and silicon are semiconductors because in the pure state they ________ poorly.

Your Answers Should Be:

A5-15. Germanium and silicon have a **single** crystal structure.

A5-16. Both germanium and silicon are semiconductors because in the pure state they **conduct** poorly.

INTRINSIC CRYSTALS

The crystals we have been examining are ideal crystals; that is, they are pure. They probably never exist in nature in such a state. Ideal crystals, or *uncontaminated* crystals, are described as *intrinsic.* The manufacture of intrinsic germanium or silicon is the first step in the making of semiconductor devices such as transistors, diodes, and microelectronic circuits.

Free Electrons in Intrinsic Crystals

Earlier we learned that the current or conductivity in semiconductor crystals is poor to fair. This applies to the nearly pure crystals found in the natural state. Why is this so? Let's go back to our study of energy bands to find the reason. Remember that the energy level of the electrons in the valence band is much lower than that of the conduction band. The covalent bonds in the crystal extend out of the valence band, not the conduction band. This is why conduction is so poor. In order to free electrons, energy must be imparted to them (Fig. 5-14). This energy moves them out of the valence band and into the conduction band.

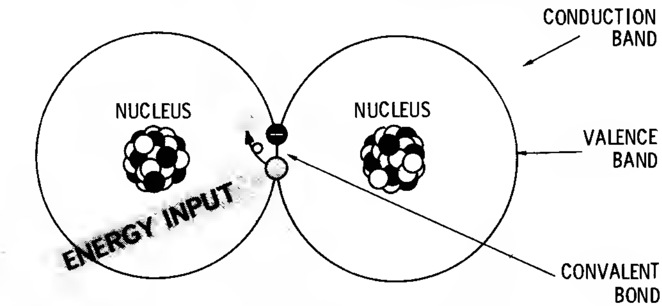


Fig. 5-14. Free electrons in intrinsic crystals.

Electron Flow in Intrinsic Germanium

Suppose we look at a particular type of crystal, like germanium, in its intrinsic state. We can assume that it has free electrons within its boundaries. These, of course, have been liberated very much as we have described. If we place a potential across this crystal we will find that an electrical current is generated but it is quite low. Remember that in metallic crystals the electron cloud essentially supplied the free electrons for current. This was so because these electrons had attained sufficient energy levels to exist in the conduction band. In semiconductor crystals, however, that is not so. Therefore, current depends on the randomly freed electrons only, and not on the valence electrons. Because the forbidden band is much smaller for semiconductors than it is for insulators, stray thermal energy or radiation often causes electrons to jump the gap into the conduction band.

Note in Fig. 5-15 how electrons flow. Thermal energy has released an electron in position 1. An electron from position 2 fills the hole left by the first electron. The one from position 3 fills the hole at position 2, and finally the electron from position 4 fills the number 3 position hole. Electrons have drifted from 4 to 3 to 2 to 1.

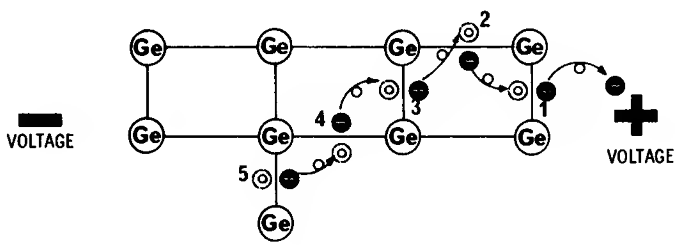


Fig. 5-15. Electron flow in intrinsic germanium.

Q5-17. Crystals without impurities are described as __________.

Q5-18. Free electrons can exist in intrinsic crystals if they absorb enough energy to move them into the ________ ________.

Q5-19. Electrons flow in intrinsic germanium when they move into ________ vacated by preceding electrons.

Your Answers Should Be:

A5-17. Crystals without impurities are described as **intrinsic.**

A5-18. Free electrons can exist in intrinsic crystals if they absorb enough energy to move them into the **conduction band.**

A5-19. Electrons flow in intrinsic germanium when they move into **holes** vacated by preceding electrons.

HOLES IN SEMICONDUCTORS

Concept of the Hole

To know how semiconductors work you must understand the concept of hole flow. For a moment, therefore, let us leave crystals and again examine a single germanium atom. You can consider the atom to be made of a nucleus and a shell of energy. For our purposes this shell may be regarded as the valence band (Fig. 5-16).

The nucleus contains 32 protons. As you know the positive effect of these 32 protons is balanced by the negative effect of 32 electrons. Four of these electrons exist in the valence band and make up the valence energy shell.

When sufficient external energy is absorbed by a valence electron it jumps the forbidden band and appears in the conduction band. The electron becomes free to move and it is no longer associated with this particular atom. The atom is left with a positive surplus due to its having one or more protons more than electrons. This *positive surplus,* represented by a missing electron, is a *hole.*

The hole in essence, may be considered a positive electron, even though it has no physical existence. It will move toward

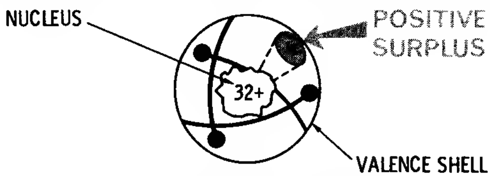


Fig. 5-16. Concept of the hole.

a negative polarity, and it will repel other holes. It is considered to have the same mass as an electron, and consequently it travels at the same velocity. A flow of holes is a flow of positive electricity.

Hole Flow in Intrinsic Germanium

Let us now return to the intrinsic germanium crystal to see how holes flow. Remember, a potential has been applied. When external energy knocked the electron out of position 1 a hole was created. A subsequent electron filled this hole (unlikes attract), but a hole appeared in position 2 from whence the electron came. This hole in turn was filled by an electron from position 3 where a new hole formed. Fig. 5-17 shows that the hole has drifted from position 1 to 2 to

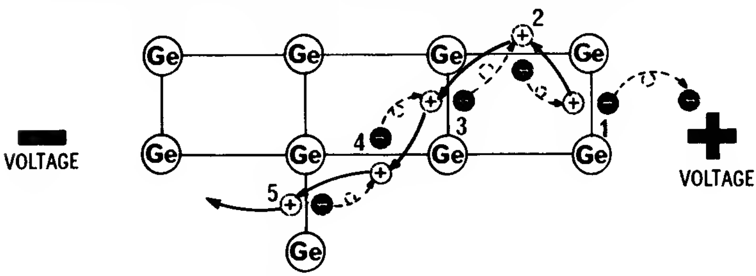


Fig. 5-17. Hole flow in intrinsic germanium.

3 to 4 to 5. Notice how the hole flows (drifts) from the positive toward the negative voltage. This is similar to the way the electron flows except that the latter flows from a negative to a positive voltage.

Q5-20. When an electron leaves the valence band a ________ is produced in the valence shell.

Q5-21. This hole has a(an) ________ electrical effect.

Q5-22. Holes may be considered positive ________.

Q5-23. Holes flow toward a ________ potential.

Your Answers Should Be:

A5-20. When an electron leaves the valence band a **hole** is produced in the valence shell.

A5-21. This hole has a **positive** electrical effect.

A5-22. Holes may be considered positive **electrons.**

A5-23. Holes flow toward a **negative** potential.

SEMICONDUCTOR MATERIALS

Impurities

The semiconductor crystals which we have studied are basically neutral electrically. They have no free electrons as in the case of metallic crystals. Only when external energy penetrates the lattice do electrons break free, but their number is comparatively small. Even with a large amount of thermal energy and a high potential applied, their current yield is quite low.

If certain elements are added to them, crystals can be made to pass higher currents. These additives are called impurities. The process of adding impurities to semiconductor crystals is called *doping*. There are two types of impurities. One produces free electrons, and the other produces holes. The electron-producing impurity is known as an N-type (negative) impurity and the hole-producing impurity is known as a P-type (positive) impurity.

N-Type Germanium

Look at the germanium (Ge) crystal (Fig. 5-18) which has been doped with arsenic (As). Arsenic is pentavalent, which means it has five valence electrons. You know that cubic germanium crystals are formed of body-centered cells. Each germanium atom therefore associates with four surrounding atoms. However, in the doping process the arsenic

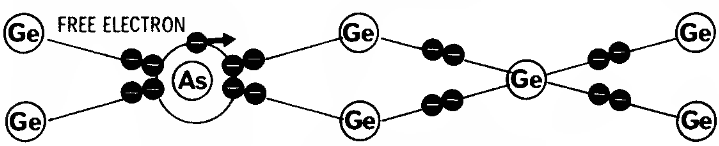


Fig. 5-18. N-type germanium crystal lattice.

atoms substitute for some of the body-centered germanium atoms. The arsenic atom joins in covalent bonds with its four neighboring germanium atoms. However, one electron remains unpaired. Sufficient thermal energy exists at room temperature to raise the electron's energy level to place it in the conduction band. Thus, it becomes free to produce current.

Donors and Majority Carriers

In the preceding example the arsenic donated an electron. The arsenic atom is called a *donor*. The entire germanium crystal is N-type, because it has a surplus of electrons to carry current. For this reason the electrons are called *majority carriers* in N-type germanium.

In the natural state, intrinsic germanium might contain one impurity atom for every 100 million germanium atoms. When it is doped, the germanium crystal might contain one donor atom for every 10 million germanium atoms. So you can see that the donor accounts for ten times the number of majority carriers that exist in the intrinsic state.

You should remember that the process of making and filling holes still goes on to produce current. Of course, their contribution is but a tiny portion of the overall current. Fig. 5-19 shows the composite effect of all the current due to the separate effects of the carriers. Note that in the case of N-type germanium, holes are the minority carriers.

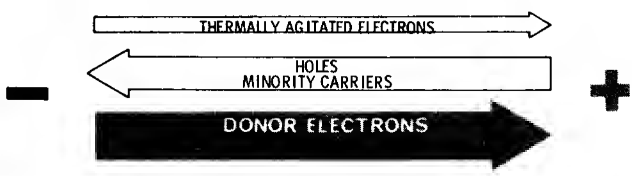


Fig. 5-19. Carriers in N-type germanium.

Q5-24. Elements added to semiconductor crystals to produce more current are called ________.

Q5-25. This process is called ________.

Q5-26. Arsenic in a germanium matrix supplies a ____ ________.

Q5-27. Doped germanium crystals with excess free electrons are called ________ crystals.

Your Answers Should Be: **A5-24.** Elements added to semiconductor crystals to produce more current are called **impurities.** **A5-25.** This process is called **doping.** **A5-26.** Arsenic in a germanium matrix supplies a **free electron.** **A5-27.** Doped germanium crystals with excess free electrons are called **N-type** crystals.

P-Type Germanium

You have just learned how arsenic makes a germanium crystal become an N type. Now, let us see how it can be doped to become a P type. This time we will dope the germanium matrix with an impurity called indium (In). This element is trivalent, that is, it has three valence electrons. Since germanium crystals form body-centered cell cubes, we find that the indium atoms substitute for some of the body-

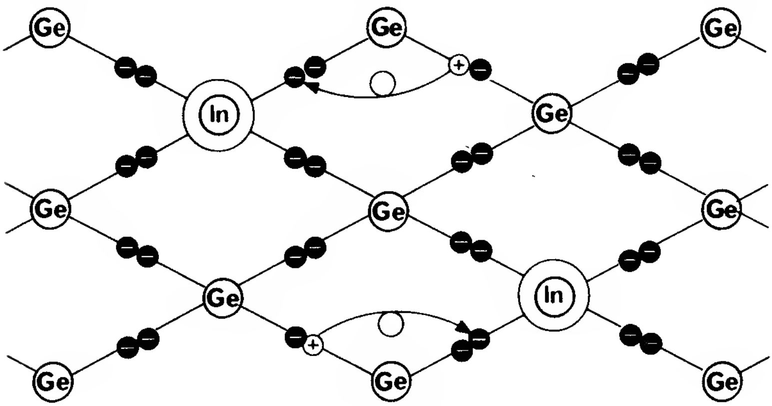


Fig. 5-20. P-type germanium crystal lattice.

centered germanium atoms. With the remaining atoms, indium forms a covalent bond by robbing an electron from the covalent pair in the next body-centered cell (Fig. 5-20). You will note that the indium now becomes completely covalent, and that the germanium is now left without an electron to form a covalent bond. This is called a *hole*. This is an unstable condition which prevails throughout the crystal.

Acceptors and Majority Carriers

In the preceding example the indium accepted an electron. The indium atom is called an *acceptor*. The entire germanium crystal is the P type, because it has a surplus of holes to carry current. For this reason these holes are called *majority carriers*.

Again, the process of making and filling holes continues to be a source of current. As in N-type crystals, the contribution to the overall current is small. Fig. 5-21 shows the composite effect of all the current due to the separate carriers. Note that in the case of P-type germanium, electrons are the minority carriers.

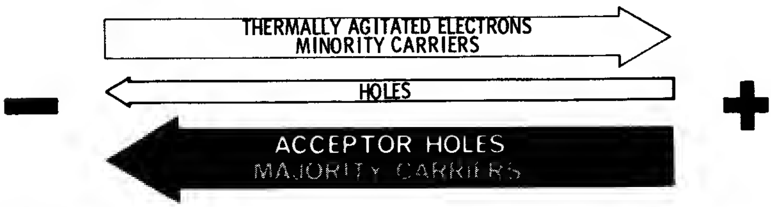


Fig. 5-21. Carriers in P-type germanium.

Q5-28. Indium in a germanium matrix robs electrons from covalent bonds to form ________ in the crystal.

Q5-29. A doped germanium crystal with an excess of free holes is known as a(an) ________-type crystal.

Q5-30. Indium is a (an) ________-type impurity.

Q5-31. The majority carriers in P-type germanium crystals are ________.

Your Answers Should Be:

A5-27. Indium in a germanium matrix robs electrons from covalent bonds to form **holes** in the crystal.

A5-28. A doped germanium crystal with an excess of free holes is known as a **P-type** crystal.

A5-29. Indium is an **acceptor**-type impurity.

A5-30. The majority carriers in P-type germanium crystals are **holes.**

P-N JUNCTION

Although N-type germanium has an excess of free electrons, this crystal is still electrically neutral. This is so because every free electron has a corresponding positively charged atom to balance it. Also, P-type germanium crystals remain electrically neutral because excess holes are exactly balanced by the electrons which they rob.

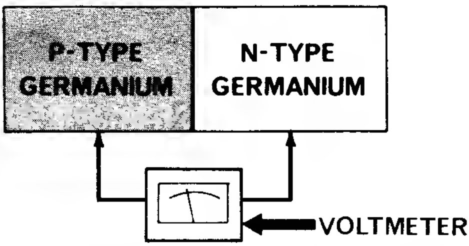


Fig. 5-22. Voltage at P-N junction.

It would seem that if you joined pieces of P-type and N-type germanium all the holes and electrons would pair up. As a result the P-N junction would simply revert to a neutral plane. But this does not happen. Instead, we find a tiny voltage in the order of a few tenths of a volt existing at the P-N junction (Fig. 5-22).

Junction Field

Let us see why this tiny voltage exists. A hole in the P type tries to diffuse into the N type. Electrons in the N type try to cross into the P type. Some holes and electrons actually pair up, but most of them encounter a barrier. This junction barrier is created by two fields.

One field is caused by the array of donor atoms which exist very close to the P-N junction. It has positive polarity and therefore tends to repel any hole that tries to diffuse into the N-type region. The other field is caused by the acceptor atoms near the P-N junction. This field exhibits negative polarity, and it tends to repel any electron that tries to cross into the P-type region. In essence, these fields are two poles of a battery—the donor atom layer being the positive pole and the acceptor atoms being the negative pole (Fig. 5-23). This is why the tiny voltage can be measured at the P-N junction.

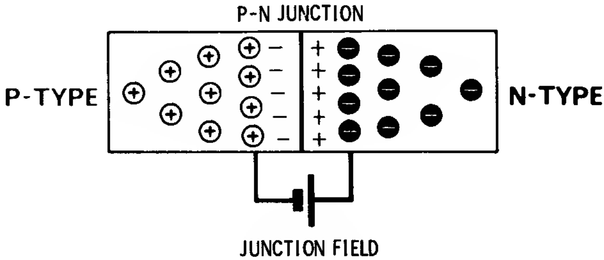


Fig. 5-23. Charge distribution at P-N junction.

The curves in Fig. 5-24 show the energy required for carriers to penetrate the junction field. Notice that for an N-type electron to diffuse into the P-type region it must absorb enough energy to buck the junction field battery. These are potential hills.

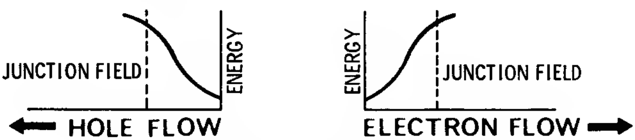


Fig. 5-24. Potential hill curves for carriers.

Q5-31. A P-N junction is evident because a tiny ______ can be measured across it.

Q5-32. Holes cannot cross into the N-type region because they are repelled by the junction ______ atoms.

Your Answers Should Be:

A5-31. A P-N junction is evident because a tiny **voltage** can be measured across it.

A5-32. Holes cannot cross into the N-type region because they are repelled by the junction **donor** atoms.

Reverse Bias

What happens if we connect a battery across a P-N junction? Suppose the battery is connected so that its positive terminal contacts the N-type region, and its negative terminal contacts the P-type region (Fig. 5-25). Immediately, the electrons are attracted to the positive terminal, and the holes are attracted to the negative terminal. The effect of this is to deplete the P-N junction of carriers.

Consider the N-type region. Do you remember that we said the crystal was electrically neutral? But, if electrons are drawn from this region an electrical imbalance occurs. As a result the N-type region tends to become positive, because there are more donor atoms than electrons. Now look at the P-type region. The drawing away of holes from this crystal causes an overly negative effect. This is because more acceptor atoms exist than holes.

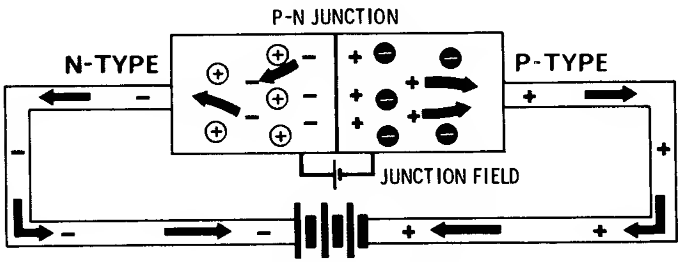


Fig. 5-25. Reverse biasing.

The increased negative effect in the P-type region repels electrons more vigorously than before. The increased positive effect in the N-type region repels holes with more vigor. This, in effect, produces a wider junction field, and current drops virtually to zero. This effect is called reverse biasing.

Forward Bias

If we reverse the battery leads, what will occur? Immediately electrons are repelled into the N-type region from the battery negative terminal, and the holes are repelled into the P-type region (Fig. 5-26). This adds energy to the electrons and holes. The absorbed energy is more than enough to surmount the potential hills. Therefore, holes and electrons combine quite readily at the P-N junction. The junction field vanishes.

Because there exists a surplus of electrons in the N-type region and because the battery positive terminal attracts them, electrons flow heavily. This way of connecting the battery to the P-N junction is known as forward biasing.

Actually, current is developed by mass hole-electron recombination. You can see this going on at the P-N junction as well as the battery positive terminal.

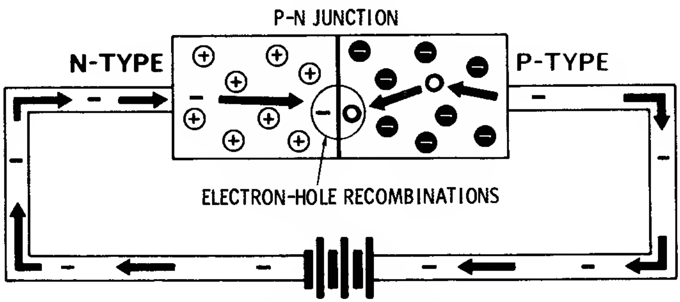


Fig. 5-26. Forward biasing.

Q5-33. When a battery connected across a P-N junction causes virtually zero current, we say that the junction is __________-__________.

Q5-34. When a battery connected across a P-N junction causes high current, we say that the junction is __________-__________.

Your Answers Should Be:

A5-33. When a battery connected across a P-N junction causes virtually zero current, we say that the junction is **reverse-biased.**

A5-34. When a battery connected across a P-N junction causes a high current, we say that the junction is **forward-biased.**

Diodes

The unusual characteristics of the P-N junction make it useful in electronics. We use it as a diode rectifier. The electronic symbol is shown in Fig. 5-27. Notice the electron-flow direction. The cathode is the N-type material, because it is the source of electrons. The anode is the P-type material, because it is the destination of the electrons.

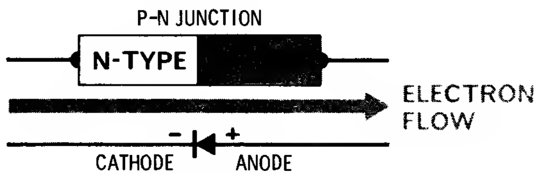


Fig. 5-27. The diode.

Remember that current generation is a matter of recombination. In the N-type region (the cathode) electrons are the majority carriers. In the P-type region (the anode) holes are the majority carriers. The absence of the junction field due to forward biasing allows the majority carriers to recombine. This is a continuous process—the battery negative terminal supplying electrons; the battery positive terminal supplying the holes.

Diodes have limitations, such as temperature. As temperature rises, resistance to current drops (negative temperature coefficient), even when the diode is reverse-biased. Current naturally depends on applied voltage. When this voltage overcomes the junction field voltage the diode acts like a conductor. When it is reverse-biased, the diode exhibits resistance but it can break down if the applied voltage is too great.

Half-Wave Rectifier

One of the most important uses to which diodes are put is rectification. Rectification simply means changing alternating current to direct current. The diode provides this kind of current (Fig. 5-28). If, instead of a battery, an a-c generator is placed across a diode, the generator forward-biases and reverse-biases the diode at the generator frequency. When the generator voltage is positive, as in 1, the

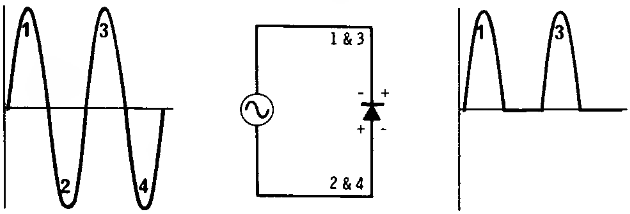


Fig. 5-28. Half-wave rectification.

diode is forward-biased and it conducts. Therefore, it puts out current which rises and falls in the same manner as the applied voltage. When the generator voltage goes negative, as in 2, it reverse-biases the diode; hence, no current. The result is a pulsating direct current every half cycle.

In Fig. 5-29 is a typical rectifier circuit. A transformer (about which you will learn in the next chapter) replaces the a-c generator. A load resistor has been added. The operating principles are identical. When point A voltage goes negative, point B is positive. This forward-biases the diode and there is current through the resistor. When the voltage reverses the diode cuts off.

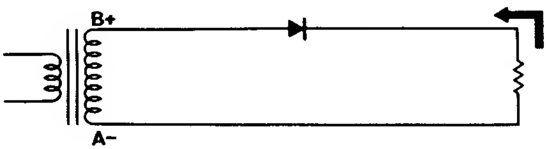


Fig. 5-29. Half-wave rectifier circuit.

Q5-35. When a-c voltage __________-biases a diode, there is current.

Your Answer Should Be:

A5-35. When a-c voltage forward-biases a diode there is current.

Full-Wave Rectifier

Another commonly used circuit which includes diodes is the full-wave rectifier. In Fig. 5-30 an a-c generator has a diode connected to each output lead. It also has a ground line. Two load resistors have been added to complete the circuit to ground.

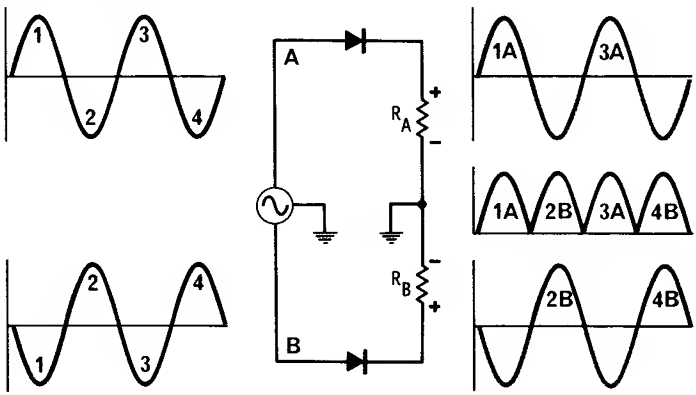


Fig. 5-30. Full-wave rectification.

When generator lead voltage A goes positive as in 1, diode A forward-biases, and it allows electrons to flow through its load resistor to ground, and from there back to the generator. The current through the resistor for this half cycle is as shown as 1A. At the same time, generator B lead voltage is negative, and reverse-biases diode B to prevent electron flow through it for this half cycle.

When lead A voltage goes negative, B-lead voltage is positive by comparison at 2. Therefore diode B forward-biases and conducts. Electrons flow through its load resistor to ground and back to the generator for this half cycle, as to 2B. At the same time, diode A is reverse-biased, preventing electron flow through it for this half cycle. The sum of the output across both load resistors is a series of half-cycle

width positive pulses of unidirectional current. This repeats for the next cycle. Note that each half-cycle, whether positive or negative, results in a positive output pulse. For this reason the circuit is called a *full-wave rectifier.*

Full-Wave Rectifier Application

Fig. 5-31 shows a practical application of this circuit. Generally, it is used as a d-c power supply. You will notice that the generator has been replaced by a transformer. However, its operation, as far as this circuit is concerned, is the same as we have described before. The load resistor is in the transformer center-tap line. The current or load is depicted by the positive d-c pulses.

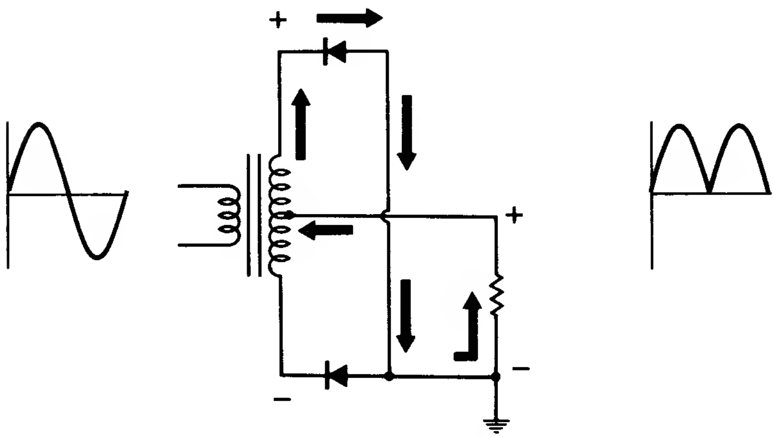


Fig. 5-31. D-c power supply.

If the load resistance varies, the load will vary in accordance with Ohm's law. For example, if a d-c power supply puts out 12 volts across a load resistor of 8 ohms, the current is found by using Ohm's law:

$$I = \frac{E}{R} \text{ or } \frac{12 \text{ volts}}{8 \text{ ohms}} = 1.5 \text{ amperes}$$

If the load resistance is changed to 12 ohms, the load becomes 1 ampere.

SUMMARY QUESTIONS

1. Energy level is another way scientists distinguish among conductors, insulators, and semiconductors.
   a. To exist in any shell, an ________ must have a certain quantity of energy.
   b. Energy levels are arranged in three bands: ________, ________, and ________.
   c. Electrons ________ exist in the forbidden band.
   d. Energy levels always differ by whole ________.

2. In a face-centered cubic lattice each face atom is surrounded by atoms.
   a. Covalent lattices are held together by ______ ______ which means that two atoms ________ a single electron.
   b. Metal crystals have many ________ electrons in the electron cloud.
   c. Germanium and silicon have ________ crystal structures.
   d. Both are semiconductors because in the pure state they conduct ________.

3. Electrons flow in intrinsic germanium when they move into holes vacated by preceding electrons.
   a. When an electron leaves the valence band, a ________ is produced in the valence shell.
   b. Holes may be considered ________ electrons.
   c. Certain elements added to semiconductor crystals to produce more current are called ________.
   d. A doped germanium crystal with an excess of free holes is known as ________ germanium.

4. A P-N junction is evident because a tiny voltage can be measured across it.
   a. When a battery connected across a P-N junction causes virtually zero current, we say that the junction is ________.
   b. When a battery connected across a P-N junction causes a high current we say that the junction is _____.
   c. Forward biasing is really a mass electron-hole ______.

5. The rectifier circuit is a practical application of diodes.
   a. Diodes change ________ current to ________ current in rectifier circuits.
   b. A half-wave rectifier gives direct current on every ________ ________ cycle.
   c. A full wave rectifier gives direct current on ________ half cycle.

SUMMARY ANSWERS

1a. To exist in any shell an **electron** must have a certain quantity of energy.
1b. Energy levels are arranged in three bands: **valence, forbidden,** and **conduction.**
1c. Electrons **cannot** exist in the forbidden band.
1d. Energy levels always differ by whole **integers.**
2a. Covalent lattices are held together by **covalent bonds** which means that two atoms **share** a single electron.
2b. Metal crystals have many **free** electrons in the electron cloud.
2c. Germanium and silicon have **single** crystal structures.
2d. Both are semiconductors because in the pure state they conduct **poorly.**
3a. When an electron leaves the valence band a **hole** is produced in the valence shell.
3b. Holes may be considered **positive** electrons.
3c. Certain elements added to semiconductor crystals to produce more current are called **impurities.**
3d. A doped germanium crystal with an excess of free holes is known as **P-type** germanium.
4a. When a battery connected across a P-N junction causes virtually zero current, we say that the junction is **reverse-biased.**
4b. When a battery connected across a P-N junction causes a high current we say the junction is **forward-biased.**
4c. Forward biasing is really a mass electron-hole **recombination.**
5a. Diodes change **alternating** current to **direct** current in rectifier circuits.
5b. A half-wave rectifier gives direct current on every **other half** cycle.
5c. A full-wave rectifier gives direct current on **every** half cycle.

6

Inductance and Capacitance in A-C Circuits

What You Will Learn

In this chapter you will learn about inductance and capacitance and how components having these electrical characteristics act in alternating-current circuits. Inductance is one of the most important properties in electrical and electronic circuits. Relays, coils, transformers, and many other devices depend on inductance for their operation. Capacitance, which blocks direct current but passes alternating current is also widely used in electrical and electronic circuits.

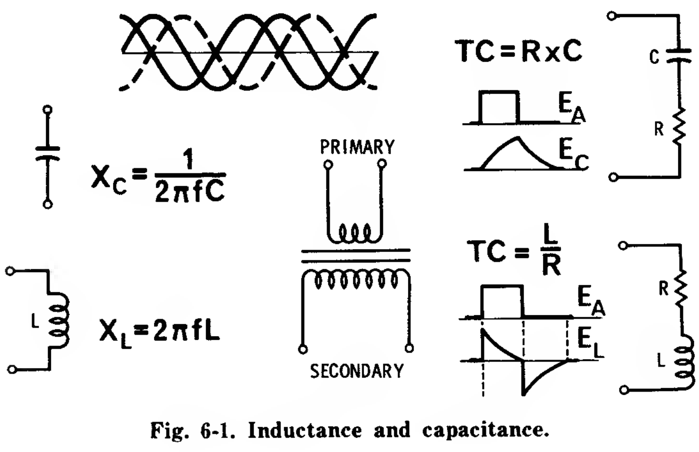


Fig. 6-1. Inductance and capacitance.

CURRENT AND MAGNETIC FIELD IN A CONDUCTOR

When there is current through a conductor, a magnetic field builds up around the conductor. As shown in Fig. 6-2, when the magnetic field builds up, its expanding lines of force cut the conductor and generate a voltage that opposes the increasing current. After the initial surge the current

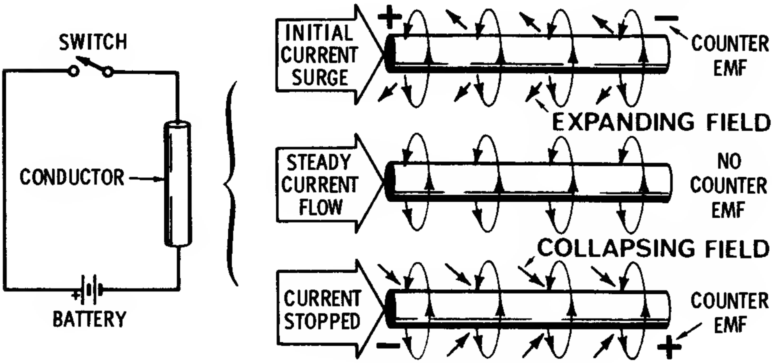


Fig. 6-2. Magnetic field in a d-c circuit.

is steady and the magnetic field is constant. Therefore, there is no counter emf generated. When the switch is opened the current stops.

This opposing voltage or *counter emf* is generated only when the current is changing. In a d-c circuit, current is changing only when the switch is either opened or closed. Therefore, the counter emf in a d-c circuit can be ignored.

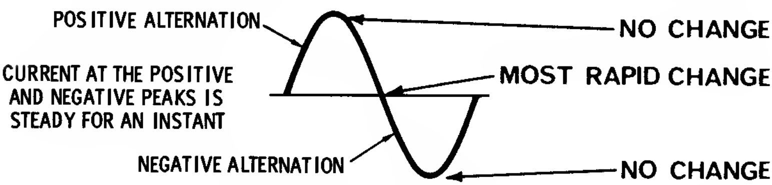


Fig. 6-3. Alternating current.

Fig. 6-3 shows that an alternating current is constantly changing. Consequently, the opposing voltage or counter emf generated by the constantly changing magnetic field is always present.

Relationship Between Applied Voltage, Current, and Counter EMF

Fig. 6-4 shows that when there is a sine wave of current through a conductor, the current is continually changing. At point A, the current is changing at its fastest rate; therefore the counter emf, trying to keep the current from increasing is at its negative peak. At point B, the current is at its positive peak and is not changing; the counter emf is at zero. At point C the current is decreasing at its maximum rate; the counter emf, trying to keep the current from decreasing, reaches its positive peak. At point D the current is at its negative peak; the counter emf is at zero.

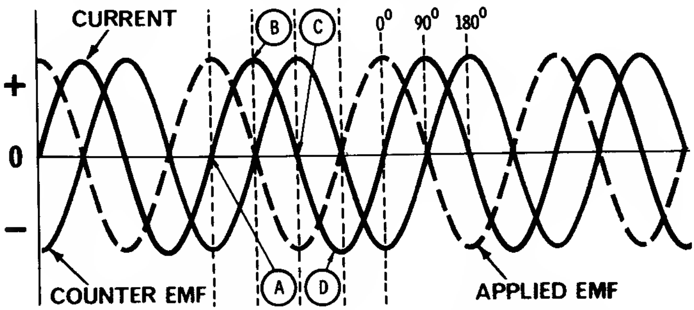


Fig. 6-4. Voltage and current phase relationships.

The following relationships exist:

1. The applied emf is 180 degrees out of phase with the induced emf. The counter emf reaches its maximum a half-cycle later than the applied emf.
2. The current lags the applied emf by 90 degrees, but leads the counter emf by 90 degrees. That is, the current reaches its maximum one quarter-cycle after the applied emf and one quarter-cycle before the counter emf.

Q6-1. The voltage generated by an expanding magnetic field is called a ________ ________.

Q6-2. The counter emf is generated only when current is ________.

Q6-3. The counter emf is ________ degrees out of phase with the applied emf.

Your Answers Should Be:

A6-1. The voltage generated by an expanding magnetic field is called a **counter emf.**

A6-2. The counter emf is generated only when current is **changing.**

A6-3. The counter emf is **180** degrees out of phase with the applied emf.

INDUCTANCE

Inductance is the property of a circuit or component to oppose any change in the current through it. In a d-c circuit, inductance has an effect only when the direct current starts, and when attempts are made to stop it. In a-c circuits, though, the voltage is constantly changing and inductance constantly acts to retard the change in current.

All conductors have some inductance. Straight wires have very small amounts, but the *inductor* or coil has much more. The coil or inductor therefore is the component used in electronic circuits to exhibit the property of opposing a change in current. Since it serves to stop or "choke" the flow of current, it is often called a *choke.*

Symbols and Unit of Measurement

The symbols used on schematic diagrams to represent the inductor are shown in Fig. 6-5. Also shown in Fig. 6-5 is the letter L that is used to represent inductance both on schematic diagrams and in inductance formulas.

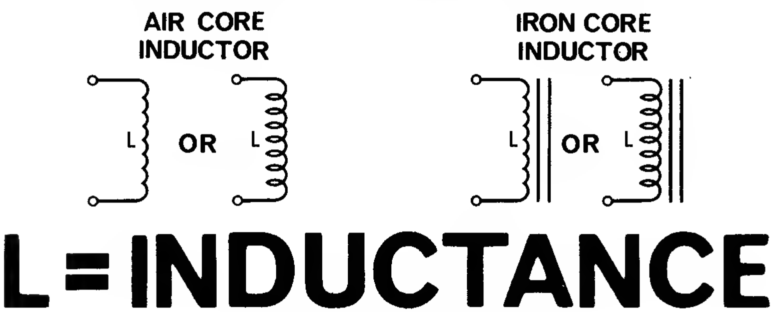


Fig. 6-5. Symbols for inductance.

The unit of measurement of inductance is the *henry*. A coil is said to have an inductance of 1 henry if a current through it, changing at a rate of 1 ampere per second, produces a counter emf of 1 volt. Fig. 6-6 shows that as current increases at a rate of 1 ampere per second, a counter emf of 1 volt is generated and opposes the increase in current. As the current decreases at the same rate, a counter emf of 1 volt of the opposite polarity is generated which will tend to sustain the current. The counter emf is constantly trying to oppose any change in current.

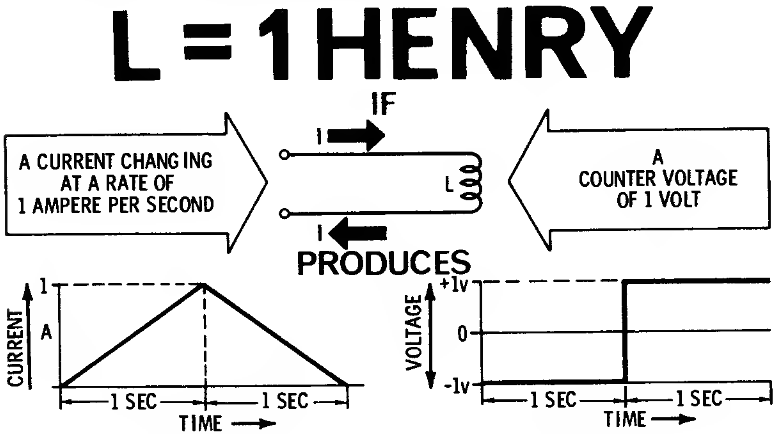


Fig. 6-6. Unit of measurement for inductance.

One henry is a very large value of inductance and will rarely be found in electronic circuits. Inductances with values in millihenrys (mh) and microhenrys (μh) are more commonly encountered in electronic equipment.

Q6-4. **Inductance opposes a change in ________ in an alternating-current circuit.**

Q6-5. **The component that exhibits the property of inductance is the ________ or ________.**

Q6-6. **The unit of measurement of inductance is the ________, but the more commonly used values of inductance are ________ and ________.**

Your Answers Should Be:

A6-4. Inductance opposes a change in **current** in an alternating-current circuit.

A6-5. The component that exhibits the property of inductance is the **inductor** or **coil.**

A6-6. The unit of measurement of inductance is the **henry,** but the more commonly used values of inductance are **millihenry** and **microhenry.**

FACTORS DETERMINING INDUCTANCE VALUE

Several factors determine the amount of inductance in a coil. The three most important factors are the number of turns or coil windings, the coil diameter, and the core material.

Number of Turns—The inductance of a coil is proportional to the square of the number of its turns. Fig. 6-7 shows that if one coil has twice the number of turns as another, it will have four times as much inductance; if it has three times as many turns it will have nine times as much inductance.

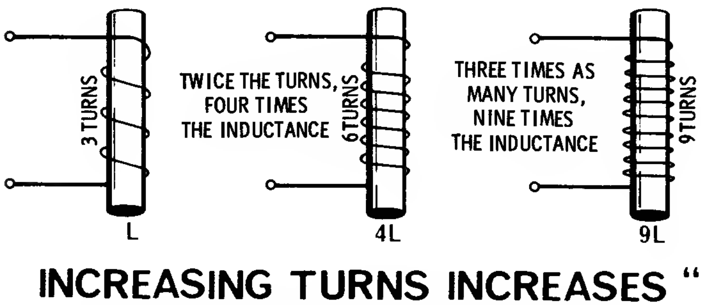


Fig. 6-7. Number of turns.

Coil Diameter—The larger the diameter of the coil, the more inductance it will have. Fig. 6-8 shows that if the diameter of one coil is twice the diameter of another, it will have twice the inductance value.

Core Material—A coil wound on an iron core or rod will have much more inductance than an air-core coil. Fig. 6-9

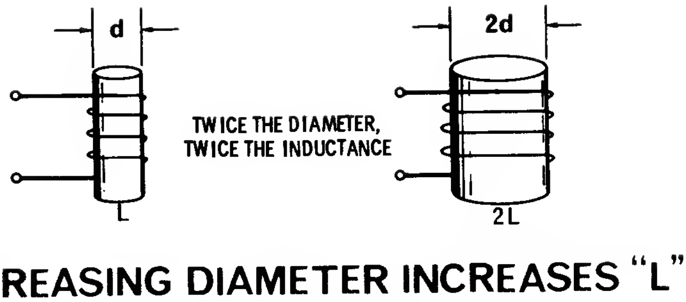


Fig. 6-8. Coil diameter.

shows that the iron-core coil has a greater value of inductance than an air-core coil of the same diameter and the same number of turns. The iron core can sustain a much greater magnetic field than air, consequently it can produce a greater inductance value. It should be noted that there is no direct ratio of increase in inductance when the iron core is added as is the case with the number of turns and the coil diameter.

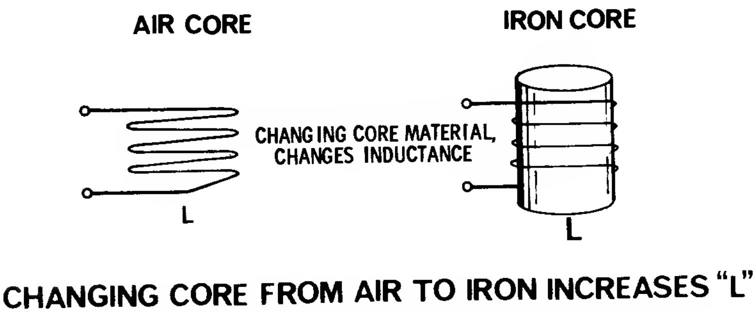


Fig. 6-9. Core material.

Q6-7. If a coil with ten turns has an inductance of 100 millihenrys, an increase to twenty turns will increase the inductance to ________ millihenrys.

Q6-8. If a coil with a diameter of one inch has an inductance of 800 millihenrys, a decrease to one-quarter inch will decrease the inductance to ________ millihenrys.

Q6-9. An air-core coil will have a ________ value of inductance than an iron-core coil.

Your Answers Should Be:

A6-7. If a coil with ten turns has an inductance of 100 millihenrys, an increase to twenty turns will increase the inductance to **400** millihenrys.

A6-8. If a coil with a diameter of one inch has an inductance of 800 millihenrys, a decrease to one-quarter inch will decrease inductance to 200 millihenrys.

A6-9. An air-core coil will have a **lower** value of inductance than an iron-core coil.

PHASE RELATIONSHIP IN AN INDUCTIVE CIRCUIT

The phase relationship between the voltage applied to a circuit and the current through the circuit indicates the time interval that elapses before the applied voltage produces a current.

Resistive Circuit

If a sine-wave voltage is applied across a resistor as shown in Fig. 6-10, the current through the resistor is also a sine wave. At every instant of the voltage sine wave, the current is determined by Ohm's law and equals E/R. The two sine waves, voltage and current, are exactly in step with each other, or *in phase*. In a resistive circuit current and voltage are always in phase.

Inductive Circuit

As explained earlier, inductance opposes any change in current. The sine wave of a-c voltage is continuously changing, therefore it is trying to change the direction of the

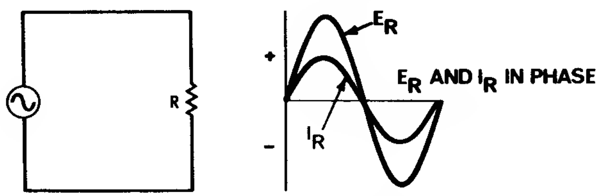


Fig. 6-10. Voltage-current phase relationship in resistive circuit.

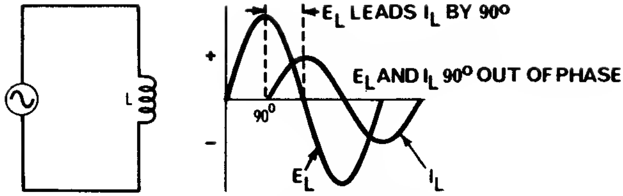
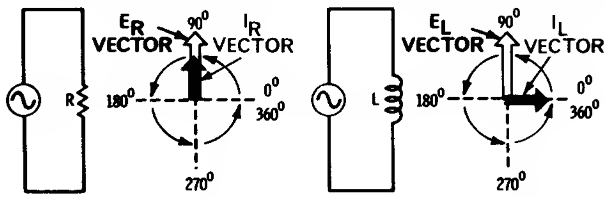


Fig. 6-11. Voltage-current phase relationship in inductive circuit.

current through an inductance. This means that inductance acts continuously to oppose any change in current when a sine wave of a-c voltage is applied. This inductive effect results in a current wave that is delayed after the applied voltage wave, as shown in Fig. 6-11. The current wave *lags* the voltage wave by exactly 90 degrees in an inductive circuit, or by one-quarter of the period of the sine wave. That is, the voltage reaches its peak 90 degrees before the current does. The two waveforms are *out of phase* by 90 degrees.

Vector Analysis

Fig. 6-12 shows the vector relationships between current and voltage in both resistive and inductive circuits. In the resistive circuit (Fig. 6-12A), it can be seen that current and voltage are in phase. In the inductive circuit (Fig. 6-12B), the current vector is 90 degrees behind the voltage vector. The length of each vector represents its magnitude.



(*A*) *Resistive circuit.* (*B*) *Inductive circuit.*

Fig. 6-12. Vector analysis.

Q6-10. The current sine wave in a resistive circuit is __________ __________ with the voltage sine wave.

Q6-11. The current sine wave in an inductive circuit __________ the voltage sine wave.

Q6-12. The current wave lags the voltage wave in an inductive circuit by __________ degrees.

Your Answers Should Be:

A6-10. The current sine wave in a resistive circuit is **in phase** with the voltage sine wave.

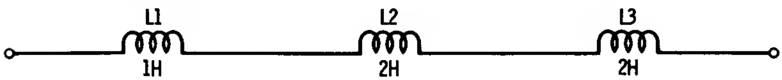
A6-11. The current sine wave in an inductive circuit **lags** the voltage sine wave.

A6-12. The current wave lags the voltage wave in an inductive circuit by **90** degrees.

SERIES, PARALLEL, AND SERIES-PARALLEL CONNECTED INDUCTORS

Series Inductive Circuit

When two or more inductors are connected in series, as shown in Fig. 6-13, the total value of inductance is determined by simply adding the individual inductance values. The formula for determining total inductance, it should be noted, is the same as that for determining total resistance in a series circuit.



$$L_T = L1 + L2 + L3 = 1H + 2H + 2H = 5H$$

Fig. 6-13. Inductance for inductors in series.

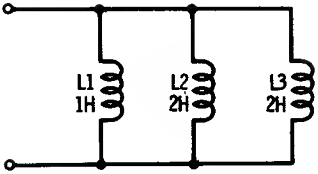
Parallel Inductive Circuit

When two or more inductors are connected in parallel, formulas for determining total inductance are the same as those used for determining total resistance.

When two inductors are of unequal value the *product over sum* method is used, as shown in Fig. 6-14B. For inductors of equal value the method which is shown in Fig. 6-14C is used.

Series-Parallel Inductive Circuit

Fig. 6-15 shows the method used to determine total inductance in a series-parallel inductive circuit.

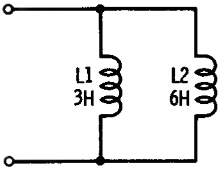


$$\frac{1}{L_T} = \frac{1}{L1} + \frac{1}{L2} + \frac{1}{L3}$$

$$\frac{1}{L_T} = \frac{1}{1H} + \frac{1}{2H} + \frac{1}{2H} = 2$$

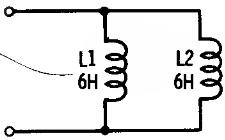
$$L_T = \frac{1}{2}H$$

(*A*) *Two or more inductors.*

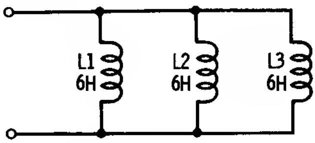


$$L_T = \frac{L1L2}{L1+L2} = \frac{3H \times 6H}{3H+6H} = 2H$$

(*B*) *Two unequal inductors.*



$$L_T = \frac{\text{ONE L}}{\text{NO. OF L's}}$$

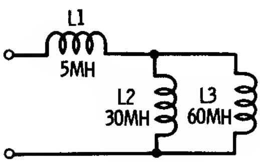


$$L_T = \frac{6H}{2} = 3H$$

$$L_T = \frac{6H}{3} = 2H$$

(*C*) *Equal inductors.*

Fig. 6-14. Inductance for inductors in parallel.



$$L_T = L1 + \frac{L2L3}{L2+L3}$$

$$L_T = 5MH + \frac{30MH \times 60MH}{30MH + 60MH} = 25MH$$

Fig. 6-15. Inductance for series-parallel inductors.

Q6-13. **Two inductors, one 350 millihenrys and the other 250 millihenrys, connected in series have a total inductance value of ________ millihenrys.**

Q6-14. **Two inductors of 500 millihenrys connected in parallel have a total inductance of ________ millihenrys.**

Q6-15. **The total inductance of two parallel-connected inductors is always ________ than the inductor with the lowest value.**

Your Answers Should Be:

A6-13. Two inductors, one 350 millihenrys and the other 250 millihenrys, connected in series have a total inductance value of **600** millihenrys.

A6-14. Two inductors of 500 millihenrys connected in parallel have a total inductance of **250** millihenrys.

A6-15. The total inductance of two parallel-connected inductors is always **less** than the inductor with the lowest value.

INDUCTIVE REACTANCE

The opposition of a resistor to current in a circuit is called resistance and is measured in ohms. The opposition of an inductor to current in an a-c circuit is called inductive reactance and is also measured in ohms.

Symbol

The symbol for inductive reactance is X_L. The letter X is used to denote reactance and the L indicates that it is the reactance offered by a coil or inductor. Reactance differs from resistance in that it is the opposition to alternating current, and the opposition will vary with the frequency of the a-c voltage applied to the coil or inductor.

Formula

The formula for inductive reactance is shown in Fig. 6-16. Inductive reactance (X_L) is measured in ohms, L is the inductance in henrys, and f is the frequency in hertz.

$$X_L = 2\pi f L$$

INDUCTIVE REACTANCE (MEASURED IN OHMS)
TWO PI (CONSTANT OF 6.28)
FREQUENCY (HERTZ)
INDUCTANCE (HENRYS)

Fig. 6-16. Formula for inductive reactance.

It can be seen from the formula and from Fig. 6-17 that X_L increases when frequency increases, or decreases when frequency decreases. When the frequency of the applied voltage increases, the current through the coil is reversing faster, causing the opposition to this change in current to increase.

$$X_L = 2\pi f L$$

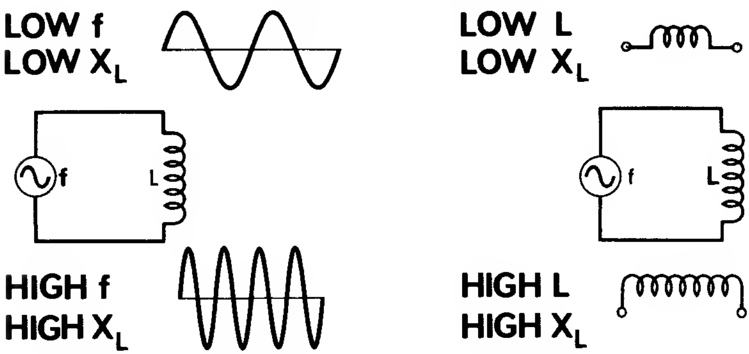


Fig. 6-17. Effect of frequency and inductance on X_L.

It can also be seen that if the value of the inductor is increased, X_L will increase, but if the value of the inductor is decreased, X_L also will decrease. With a larger value of inductance, more opposition to the change in current exists; consequently, X_L is greater.

Inductance is very useful because every inductive circuit is *frequency-sensitive*. This principle is used in filters, antennas, and many other applications. An inductive circuit passes direct current and low-frequency alternating current, but impedes the higher-frequency current.

Q6-16. **The symbol used to represent inductive reactance is ________.**

Q6-17. **Inductive reactance depends on the value of inductance and ________.**

Q6-18. **The unit of measurement for inductive reactance is the ________.**

Your Answers Should Be:

A6-16. The symbol used to represent inductive reactance is $\mathbf{X_L}$.

A6-17. Inductive reactance depends on the value of inductance and **frequency.**

A6-18. The unit of measurement for inductive reactance is the **ohm.**

FILTERS

Because inductive reactance depends on frequency, inductance is often used in filters—special circuits that have the property of allowing certain frequencies to pass while blocking others. There are, for example, *low-pass filters* which pass low frequencies; *high-pass filters* which pass frequencies that are above a predetermined frequency; and *band-pass filters* which pass only a certain band of frequencies.

Low-Pass Filter

The low-pass filter shown in Fig. 6-18 has an inductor in series with the input and output terminals of the circuit. When the input frequency is low, the inductive reactance of the coil is low, allowing the low input frequency to appear at the output of the circuit. As the input frequency increases, the inductive reactance of the coil increases; consequently, less and less of the input appears at the output.

High-Pass Filter

The high-pass filter shown in Fig. 6-19 has an inductor in parallel with the output terminals of the circuit. When

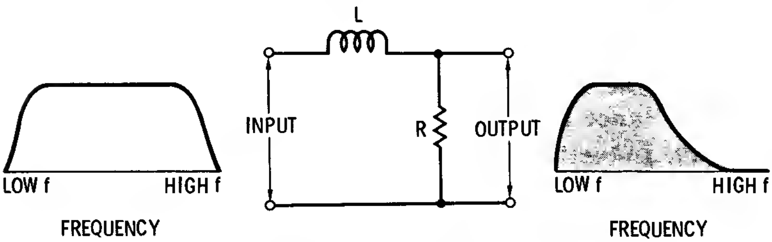


Fig. 6-18. Low-pass filter.

the input frequency is low, the inductive reactance of the coil is low, acting as a shunt across the output. Practically none of the input voltage appears at the output. As the input frequency increases, the inductive reactance of the coil increases, causing more and more of the input to appear at the output of the circuit.

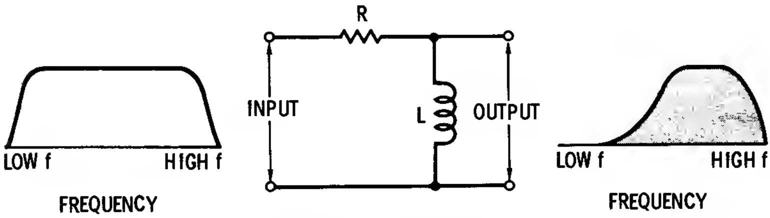


Fig. 6-19. High-pass filter.

Bandpass Filter

The bandpass filter shown in Fig. 6-20 will not be discussed here. The operation of this circuit depends on a condition called resonance which will be discussed later in this chapter.

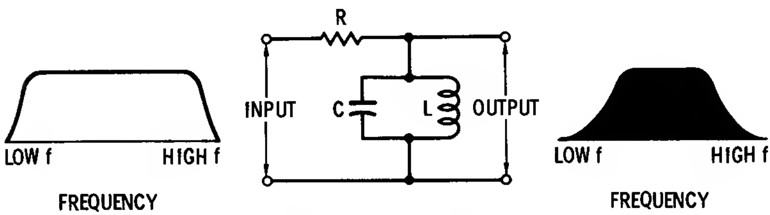


Fig. 6-20. Bandpass filter.

Q6-19. The filter that allows only high frequencies to pass is called a ________ filter.

Q6-20. The filter that blocks high frequencies and allows only low frequencies to pass is the ________ filter.

Q6-21. The filter that allows only a band of frequencies to pass is the ________ filter.

Your Answers Should Be:

A6-19. The filter that allows only high frequencies to pass is called a **high-pass** filter.

A6-20. The filter that blocks high frequencies and allows only low frequencies to pass is the **low-pass** filter.

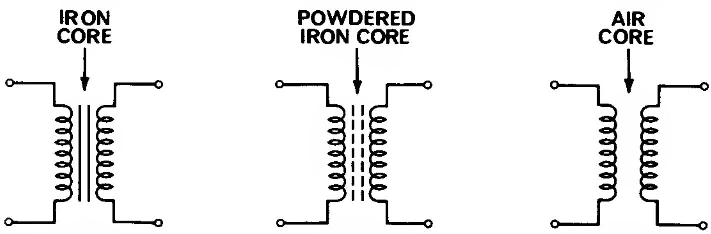
A6-21. The filter that allows only a band of frequencies to pass is the **bandpass** filter.

TRANSFORMERS

The device that transfers power from one voltage-current level to another voltage-current level is called the *transformer.* The transformer operates on the principle of the moving magnetic field and the fact that as the magnetic field cuts a conductor it can induce a voltage in that conductor.

Symbols

The schematic symbol used to represent the transformer will differ slightly depending on its application. Fig. 6-21



(*A*) *Power transformer.* (*B*) *Intermediate-frequency transformer.* (*C*) *High-frequency transformer.*

Fig. 6-21. Transformer symbols.

shows the three schematic symbols. The power transformer, used primarily in power applications such as power supplies, uses an iron core. The intermediate-frequency transformer, used at radio frequencies, has a powdered iron core. The high-frequency transformer, used at high radio frequencies, has an air core.

Transformer Operation

The transformer shown in Fig. 6-22 operates on the principle that as an a-c voltage is applied to the *primary* winding, the magnetic field will expand and collapse at the rate of the frequency of the applied voltage. As the magnetic field expands, a voltage of the opposite polarity of the primary voltage will be induced in the *secondary* winding. As the magnetic field of the primary collapses, a voltage of the opposite polarity is induced in the secondary due to the change in the direction of the collapsing magnetic field. It can be seen that the frequency of the induced voltage is exactly the same as the primary voltage and that the secondary voltage is 180 degrees out of phase with the primary voltage.

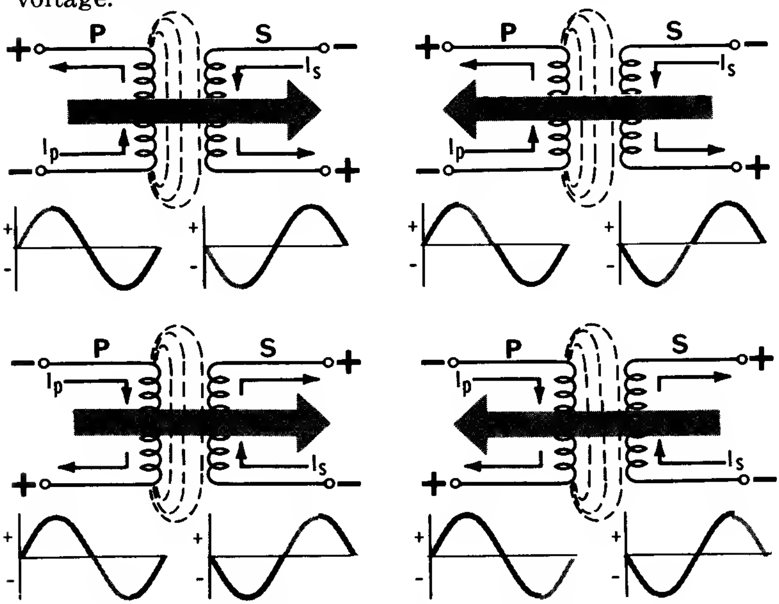


Fig. 6-22. Transformer operation.

Q6-22. The schematic symbol for a transformer can have ________ different configurations.

Q6-23. The transformer winding into which a voltage is induced is the ________ winding.

Q6-24. The transformer primary and secondary voltages are ________ degrees out of phase.

Your Answers Should Be:

A6-22. The schematic symbol for a transformer can have **three** different configurations.

A6-23. The transformer winding into which a voltage is induced is the **secondary** winding.

A6-24. The transformer primary and secondary voltages are **180** degrees out of phase.

Factors Affecting Induced Voltage

One of the main advantages of using transformers is that they can change voltage. The amount of voltage induced in the secondary winding (E_S) of the transformer is not always the same as the voltage applied to the primary (E_P). The secondary voltage depends on the number of turns in

$$\frac{T_S}{T_P} = \frac{E_S}{E_P}$$

Fig. 6-23. Voltage-turns ratio.

the secondary (T_S) as compared to the number of turns in the primary (T_P). Fig. 6-23 shows the relationship between the number of turns in the secondary as compared to the primary. This ratio is called the *turns ratio*. The *voltage ratio* is the ratio of secondary voltage to primary voltage.

Step-Up Transformer

The step-up transformer shown in Fig. 6-24 has a turns ratio that induces a greater voltage in the secondary winding than is applied to the primary winding. Whenever more voltage is induced in the secondary than is applied to the primary, the transformer is called a *step-up transformer*.

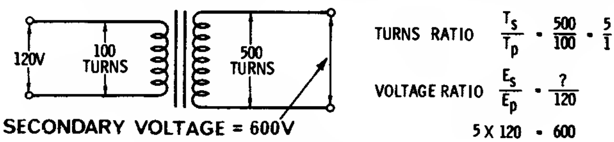
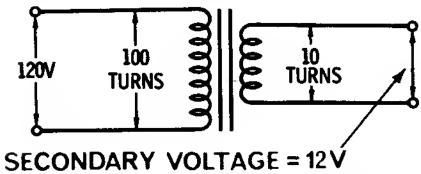


Fig. 6-24. Step-up transformer.

Step-Down Transformer

The step-down transformer shown in Fig. 6-25 has a turns ratio that provides less voltage in the secondary than is applied to the primary. As with the step-up transformer, the primary-to-secondary turns ratio determines the amount of voltage induced into the secondary winding.



TURNS RATIO $\frac{T_s}{T_p} = \frac{10}{100} = \frac{1}{10}$

VOLTAGE RATIO $\frac{E_s}{E_p} = \frac{?}{120}$

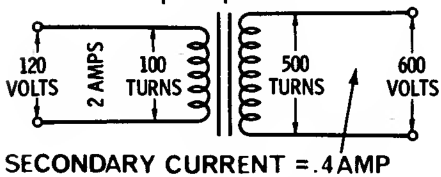
$\frac{1}{10}$ OF 120 = 12

Fig. 6-25. Step-down transformer.

Current Ratio

The *current ratio* is the relationship of primary current to secondary current. The power transfer from primary to secondary is always the same; the current ratio is the *inverse* of the voltage ratio, as shown in Fig. 6-26.

$$\frac{T_s}{T_p} = \frac{E_s}{E_p} = \frac{I_p}{I_s}$$



VOLTAGE RATIO $\frac{E_s}{E_p} = \frac{600}{120} = \frac{5}{1}$

CURRENT RATIO $\frac{I_p}{I_s} = \frac{2A}{?}$

$\frac{1}{5}$ OF 2 = .4A

Fig. 6-26. Current ratio.

Q6-25. A transformer with more voltage induced into the secondary than is applied to the primary is a ________ transformer.

Q6-26. A transformer with six turns on the primary for each secondary winding and 120 volts applied to the primary will have a secondary voltage of ________ volts.

Q6-27. A step-up transformer will have ________ secondary current than primary current.

Your Answers Should Be:

A6-25. A transformer with more voltage induced into the secondary than is applied to the primary is a **step-up** transformer.

A6-26. A transformer with six turns on the primary for each secondary winding and 120 volts applied to the primary will have a secondary voltage of **20** volts.

A6-27. A step-up transformer will have **less** secondary current than primary current.

THE PULSE RESPONSE OF INDUCTORS

When a sine-wave voltage is applied to a circuit containing an inductor, it only delays the phase relationship of the sine-wave voltage and the circuit current. When square waves or pulses are applied, however, the inductor opposes a change of current in its usual way, and in doing so distorts the waveform of the square-wave voltage.

Analysis of Inductor Current Waveform

When a pulse voltage is applied to an inductor, as shown in Fig. 6-27, the effect of the inductor is to oppose any

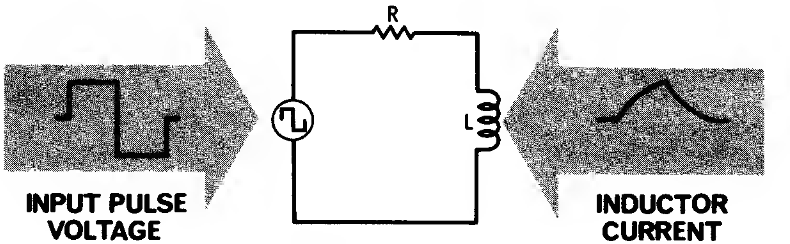


Fig. 6-27. Inductor current waveform.

change in its current condition. Therefore the pulse voltage, as it increases from zero to its most positive value instantaneously, cannot produce an instantaneous change in current from zero to its maximum value. The current will increase slowly from zero to its maximum value as the pulse voltage overcomes the opposition of the inductor (X_L).

Likewise, when the pulse input voltage decreases from its maximum value to zero, the inductor will oppose this change in its current condition; consequently, the current will drop from its maximum value to zero at a much slower rate than the pulse voltage drops from maximum to zero.

Analysis of Inductor Voltage Waveform

As is true in all electronic circuits, the voltage waveform across a component is caused by the current through it. Fig. 6-28 shows that the voltage waveform across the inductor is a greatly distorted version of the pulse input waveform.

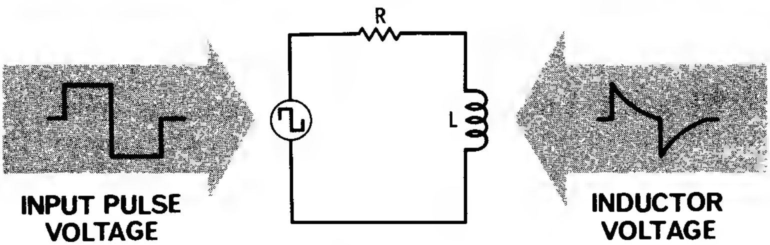


Fig. 6-28. Inductor voltage waveform.

As the input pulse increases from zero to its maximum value, the opposition (X_L) of the inductor will be at its maximum value; consequently, the voltage across the inductor will be maximum. As the input pulse voltage remains at its maximum value, the opposition of the coil decreases, causing a decrease in the voltage drop across the inductor. As soon as the pulse voltage drops from its maximum to its minimum value, the X_L of the inductor will again increase, but because the magnetic field around the inductor is now collapsing, the polarity of the voltage across the inductor will be of the opposite polarity.

Q6-28. An inductor will ________ a square-wave input voltage.

Q6-29. The inductive reactance of the inductor is at its ________ value when the pulse input voltage is changing from zero to maximum.

Q6-30. The inductor voltage will have a ________ polarity as the pulse voltage drops from maximum to zero.

Your Answers Should Be:

A6-28. An inductor will **distort** a square-wave input voltage.

A6-29. The inductive reactance of the inductor is at it's **highest** value when the pulse input voltage is changing from zero to maximum.

A6-30. The inductor voltage will have a **negative** polarity as the pulse voltage drops from maximum to zero.

IMPEDANCE

When a circuit contains only resistance, the opposition to the current can be determined by using Ohm's law ($I = E/R$). When a circuit contains only inductance, the opposition to the current again can be determined by using Ohm's law, using inductive reactance instead of resistance ($I = E/X_L$). When a circuit contains *both* resistance and inductance, the overall opposition to the current is called *impedance*. The symbol for impedance is Z.

Impedance Formula

One simple method that can be used to determine the impedance of an RL circuit is to use vectors, as shown in Fig. 6-29. The current through the resistance in an a-c circuit is in phase with the applied voltage, while the current in the inductance lags 90 degrees behind the voltage. Just as the rms value of the inductive current cannot be used to find the overall current, the 3 ohms of resistance cannot be added directly to the 4 ohms of inductive reactance. Instead, the

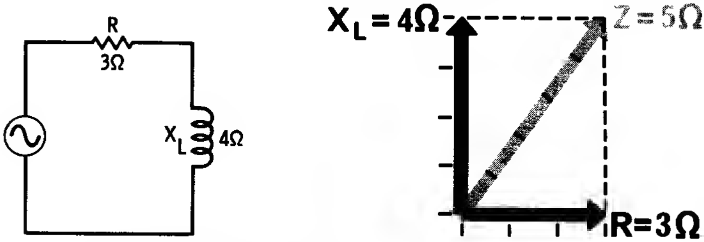


Fig. 6-29. Vector analysis to determine impedance.

overall effect of the two must be found in the same way that the overall current vector is found.

To find the overall effect of 3 ohms of resistance and 4 ohms of inductive reactance, from a point draw a vertical line 4 units long. This line represents the inductive reactance. Then from the same point draw a horizontal line 3 units long. This line represents the resistance. The two lines form two sides of a rectangle. The number of units in the diagonal of this rectangle will represent the impedance.

$$Z = \sqrt{R^2 + X_L^2}$$

IMPEDANCE = THE SQUARE ROOT OF RESISTANCE SQUARED PLUS X_L SQUARED
(OHMS)

$$\sqrt{R^2 + X_L^2} = Z$$

$$R = 3\Omega;\ X_L = 4\Omega \qquad \sqrt{9 + 16} = Z$$

$$\sqrt{25} = Z \qquad 5\Omega = Z$$

Fig. 6-30. Impedance formula.

This method can be used only when values of R and X_L are small enough to use vectors. Another more acceptable method is the use of the formula shown in Fig. 6-30. Before trying to use this formula to determine the impedance of an RL circuit it is suggested that you review the method of finding the square root of a number.

Q6-31. When both the resistance and the inductive reactance of an RL circuit are low, impedance can be found by using ________.

Q6-32. The total impedance of an RL circuit can be found by finding the square root of ________ ________ plus ________ ________.

Q6-33. The impedance of an RL circuit with 10 ohms resistance and 7 ohms inductive reactance is ________ ohms.

Your Answers Should Be:

A6-31. When both the resistance and the inductive reactance of an RL circuit are low, impedance can be found by using **vectors.**

A6-32. The total impedance of an RL circuit can be found by finding the square root of **R squared** plus **X_L squared.**

A6-33. The impedance of an RL circuit with 10 ohms resistance and 7 ohms inductive reactance is **12.2 ohms.**

INDUCTIVE CIRCUIT POWER

Inductance, unlike resistance, consumes no power. When the current in the circuit is increasing, inductance takes energy out of the circuit. It converts this energy into a magnetic field. When the current in the circuit is decreasing, however, this magnetic field collapses, and all the energy returns to the circuit.

Power in a Resistive Circuit

When an a-c voltage is applied to a resistive circuit, as shown in Fig. 6-31, the power consumed can be determined by Ohm's law. With a resistance of 20 ohms, and an applied voltage of 120 volts. the current through the circuit is 6 amperes. The power consumed is 720 watts.

The power shown in Fig. 6-31 has two positive pulses. Two important rules that you must remember are:

a. When you multiply positive values by positive values, or negative values by negative values, the results are positive values.

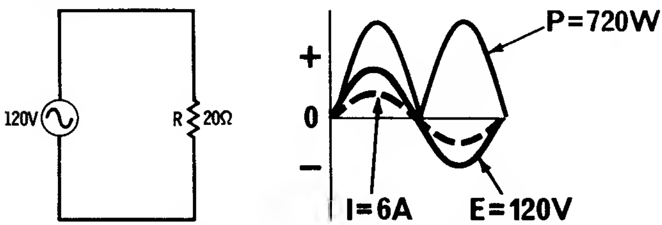


Fig. 6-31. Power in resistive circuit.

b. When you multiply positive values by negative values, the results are negative values.

Power in an Inductive Circuit

Fig. 6-32 shows the voltage, current, and power waveforms in an inductive circuit. Between points B and C both current and voltage are positive. If their values are multiplied, it appears that power is being dissipated exactly as in a resistive circuit. Between points D and E, both current and voltage are negative, and again you have exactly the same situation as in a resistive circuit—power appears to be dissipated. But, between points A and B and points C and D, there is a situation that never exists in a resistive circuit.

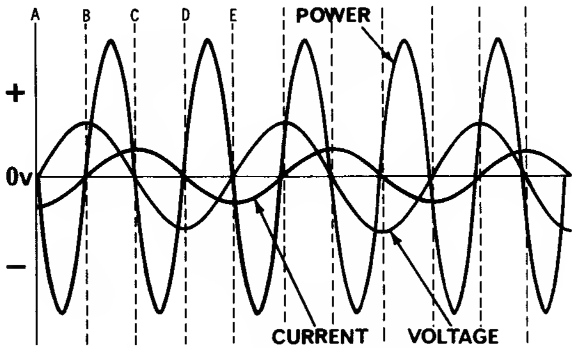


Fig. 6-32. Power in inductive circuit.

As you can see, there are pulses of negative power as well as positive power. The positive power pulses represent the time when the circuit is utilizing power to produce a magnetic field. The negative-power pulses represent the time when the circuit is absorbing power from the magnetic field. The negative pulses and the positive pulses are equal and cancel each other, so the total power dissipated is zero.

Q6-34. The voltage between points A and B of Fig. 6-32 is ________ polarity.

Q6-35. The current between points A and B of Fig. 6-32 is ________ polarity.

Q6-36. The power between points A and B of Fig. 6-32 is ________ polarity.

Your Answers Should Be:

A6-34. The voltage between points A and B of Fig. 6-32 is **positive** polarity.

A6-35. The current between points A and B of Fig. 6-32 is **negative** polarity.

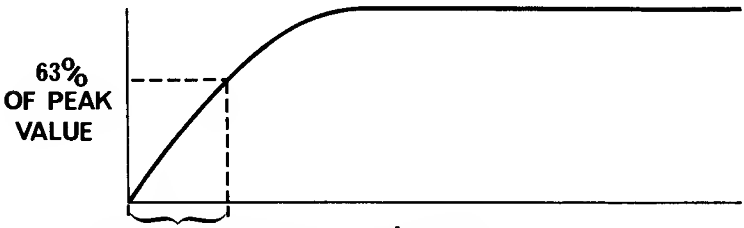
A6-36. The power between points A and B of Fig. 6-32 is **negative** polarity.

TIME CONSTANT IN RL CIRCUITS

As was explained previously, whenever a pulse voltage is applied to an RL circuit the waveshape of the input pulse will be distorted. The inductive effect of the coil, causing the change in current to lag behind the change in voltage, causes this distortion. The *time constant* of the RL circuit is the measure of the amount of time required for the current through the circuit to reach 63 percent of its maximum value when the voltage changes.

Time Constant Formula

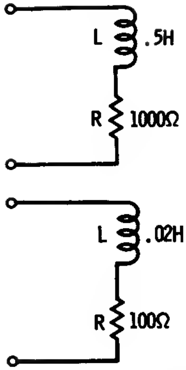
The formula for determining the length of time for current to increase to 63 percent of its maximum value is shown in Fig. 6-33.



$$\underset{\text{(SECONDS)}}{\text{TIME CONSTANT}} = \frac{L\ \text{(HENRYS)}}{R\ \text{(OHMS)}}$$

Fig. 6-33. Time constant formula.

Fig. 6-34 shows several examples of how the time constant formula is used to determine the time constant of RL networks. As the value of L increases or the value of R decreases, the time constant of the RL circuit increases.



$$TC = \frac{L}{R} = \frac{.5H}{1000\Omega} = .0005\text{sec. OR } 500\mu\text{sec.}$$

$$TC = \frac{L}{R} = \frac{.02H}{100\Omega} = .0002\text{ sec. OR } 200\mu\text{sec.}$$

Fig. 6-34. Application of time constant formula.

RL Waveforms

When a pulse of a given duration is applied to an RL circuit, the RL circuit distorts the pulse voltage waveshape. Fig. 6-35 shows waveshapes of the pulse input voltage, the inductor voltage, and the resistor voltage. The voltage across the inductor is called the *differentiated voltage;* the voltage across the resistor is the *integrated voltage.*

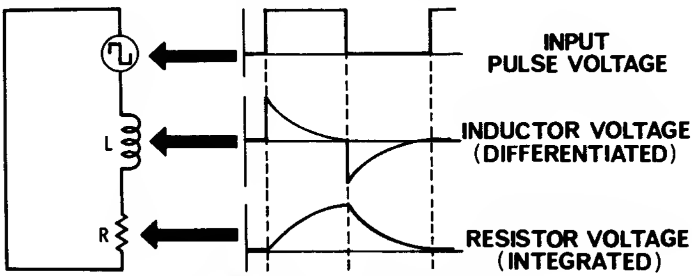


Fig. 6-35. RL circuits waveshapes.

Q6-37. The time constant of an RL circuit is the time required for current to reach ________ percent of its maximum value.

Q6-38. If the inductor value is in henrys and resistance in megohms, the time constant will be in ________.

Q6-39. The voltage waveform across the resistor of an RL circuit is the ________ voltage .

Your Answers Should Be:

A6-37. The time constant of an RL circuit is the time required for current to reach 63 percent of the maximum value.

A6-38. If the inductor value is in henrys and resistance in megohms, the time constant will be in **μseconds.**

A6-39. The voltage waveform across the resistor of an RL circuit is the **integrated** voltage.

Current in RL Circuits

As explained earlier, the current through the RL circuit will reach 63 percent of its maximum value in one time constant. Fig. 6-36 shows that five time constants are required for current to reach its maximum value. Assume a total circuit current of 10 amperes and an applied pulse voltage of 100 volts as an example.

a. During the first time constant, the circuit current will increase to 63 percent of 10 amperes, or 6.3 amperes. The voltage across the resistor will increase to 63 percent of the applied voltage or 63 volts, and inductor voltage will decrease 63 percent or to 37 volts.

b. During the second time constant, the circuit current will increase another 63 percent of the remaining value of 3.7 amperes, or an additional 2.3 amperes ($6.3 + 2.3 = 8.6$ amperes). The voltage across the re-

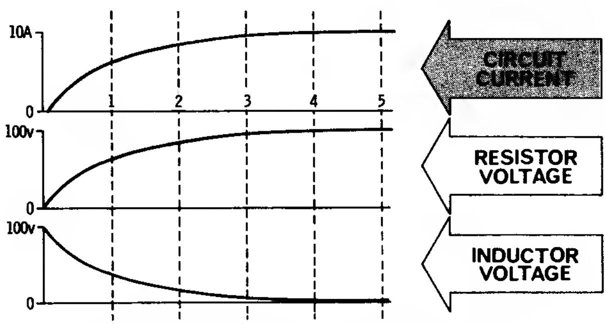


Fig. 6-36. Analysis of RL circuit current.

sistor will increase another 63 percent to 86 volts, and the inductor voltage will decrease to 14 volts.

c. During the third time constant current will increase another 63 percent or to 9.5 amperes. Resistor voltage increases to 95 volts, and inductor voltage drops to 5 volts.

d. The circuit current continues to increase 63 percent of the remaining value during the fourth and fifth time constants, until at the end of the fifth time constant, circuit current is at 10 amperes, resistor voltage is 100, and inductor voltage is zero.

Universal Time Constant Chart

The universal time constant chart shown in Fig. 6-37 can be used to calculate the rise or decay (drop) of voltage or current in any RL circuit to which a pulse voltage is applied.

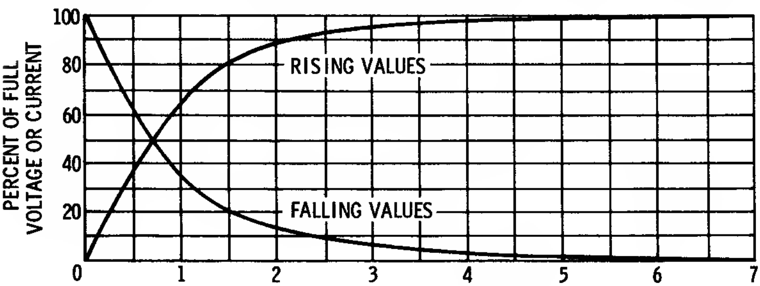


Fig. 6-37. Universal time constant chart.

The only information required to use the universal chart is the input voltage value and current value and the time constant of the circuit.

Q6-40. If L is 3 henrys and R is 5 ohms, current will reach 63 percent of its maximum value in ______ second(s).

Q6-41. If L is 2 henrys and R is 10 ohms, resistor voltage will reach 98 percent of its maximum value in ________ second(s).

Q6-42. ________ time constants are required for either circuit voltage or current to reach its maximum value.

Your Answers Should Be:

A6-40. If L is 3 henrys and R is 5 ohms, current will reach 63 percent of its maximum value in 0.6 second.

A6-41. If L is 2 henrys and R is 10 ohms, resistor voltage will reach 98 percent of its maximum value in 0.8 second.

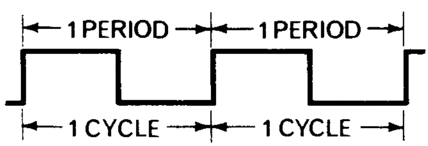
A6-42. Five time constants are required for circuit voltage or current to reach its maximum value.

TIME CONSTANT-TO-PERIOD RATIO IN RL CIRCUITS

The time constant-to-period ratio (TC-to-P) is the ratio of the pulse-duration time of the input pulse voltage to the time constant of the RL circuit. By knowing this ratio, the waveshape of the voltage across the resistor or inductor can be changed to the desired shape by changing the value of either R or L in the RL circuit.

TC-to-P Formula

The period of a pulse voltage is the amount of time, in seconds, that the pulse voltage remains at its maximum value, then drops and remains at its minimum value. In other words, it is the amount of time from the appearance of the leading edge of one pulse to the appearance of the leading edge of the next pulse. Fig. 6-38 shows the formulas for converting frequency of a pulse voltage to period, or period to frequency.



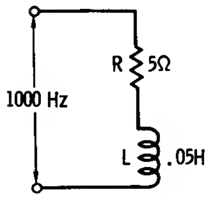
$$\underset{\text{(SECONDS)}}{\text{PERIOD}} = \frac{1}{\text{FREQUENCY}} = \frac{1}{1000\text{Hz}} = \text{P} \ .001 \text{ sec.}$$

$$\underset{\text{(HERTZ)}}{\text{FREQUENCY}} = \frac{1}{\text{PERIOD}} = \frac{1}{.001 \text{ sec.}} = \text{F} \ 1000 \text{ Hz}$$

Fig. 6-38. Period and frequency formulas.

The relationship between the time constant of the RL circuit and the period of the pulse voltage is shown in Fig. 6-39. It can be seen that the ratio between the two is obtained by dividing the time constant by the period. It must be remembered that the time constant of an RL circuit is

$$\frac{TC}{P}\ \frac{\text{(TIME CONSTANT)}}{\text{(PERIOD)}} = \frac{L/R}{P}$$



$$TC = \frac{L}{R} = \frac{.05}{5} = .01$$

$$P = \frac{1}{\text{FREQ.}} = \frac{1}{1000} = .001$$

$$\frac{TC}{P} = \frac{.01}{.001} = \frac{10}{1}$$

Fig. 6-39. Application of TC-to-P formula.

obtained by dividing the value of L by the value of R as previously explained.

The ratio of time constant to period is expressed in six general catagories as shown in Fig. 6-40.

$\frac{1}{10}$ = SHORT

$\frac{1}{1}$ = INTERMEDIATE

$\frac{1}{100}$ = VERY SHORT

$\frac{10}{1}$ = LONG

$\frac{1}{1000}$ = EXTRA SHORT

$\frac{100}{1}$ = VERY LONG

Fig. 6-40. TC-to-P ratio categories.

Q6-43. The time from the appearance of the leading edge of one pulse to the appearance of the leading edge of the next is the ________ of the pulse.

Q6-44. The relationship between the time constant and the pulse time is called the ________ ratio.

Q6-45. A pulse with a frequency of 5000 hertz would have a period of ________ second(s).

Your Answers Should Be:

A6-43. The time from the appearance of the leading edge of one pulse to the appearance of the leading edge of the next is the **period** of the pulse.

A6-44. The relationship between the time constant and the pulse time is called the **TC-to-P** ratio.

A6-45. A pulse with a frequency of 5000 hertz would have a period of **.0002** second.

RL Circuit with a Short TC-to-P Ratio

When the time constant of the RL circuit is short with respect to the period of the pulse, the following actions take place:

1. As the pulse input voltage increases from minimum to maximum, the entire input voltage is across the inductor, due to its high impedance.
2. During the long time (with respect to the TC) that the input pulse remains at its maximum value, circuit current can increase to its maximum value, causing the resistor voltage to rise to maximum, and the inductor voltage to drop to minimum.
3. As the input voltage drops to minimum, the counter emf across the inductor (due to the collapsing magnetic field) will be at its maximum negative value; resistor voltage will be at a maximum positive value.
4. As the magnetic field of the inductor collapses (during the long minimum value pulse time), the current through the resistor decreases, causing resistor voltage to drop to zero.

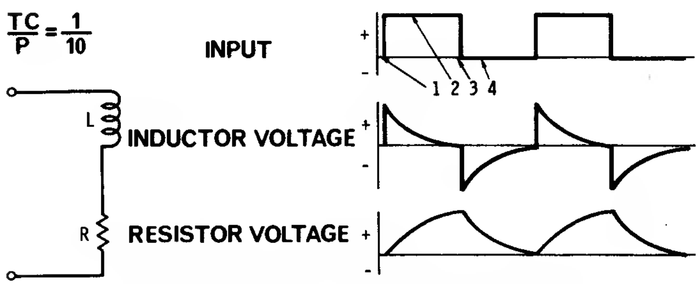


Fig. 6-41. Waveforms for short TC-to-P ratio.

RL Circuit with a Long TC-to-P Ratio

When the time constant of the RL circuit is long with respect to the period of the pulse, the following actions take place:

1. As the pulse input voltage increases from minimum to maximum, the entire input voltage is across the inductor, due to its high impedance.
2. During the short time (with respect to the TC) that the input pulse remains at its maximum value, circuit current cannot increase to its maximum value. Therefore, resistor voltage will increase to a fraction of its maximum value, and inductor voltage will drop only slightly.
3. As the input voltage drops to minimum the counter emf of the inductor will produce a voltage of negative polarity across the inductor.
4. As the magnetic field of the inductor collapses during the short time of minimum pulse value, the circuit current decreases, causing the resistor voltage to drop to zero.

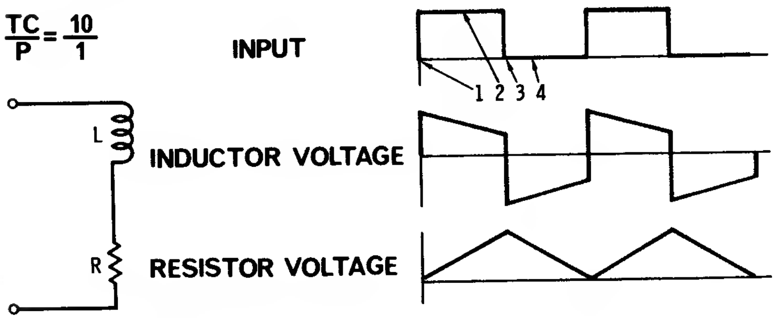


Fig. 6-42. Waveforms for long TC-to-P ratio.

Q6-46. During the input-pulse rise time (leading edge), all voltage is across the ________.

Q6-47. With a short TC-to-P ratio the resistor voltage waveshape is a ________ voltage.

Q6-48. In a long TC-to-P ratio circuit, the voltage across the resistor will be very ________.

Your Answers Should Be:

A6-46. During the input-pulse rise time (leading edge), all voltage is across the **inductor.**

A6-47. With a short TC-to-P ratio the resistor voltage waveshape is a **sawtooth** voltage.

A6-48. In a long TC-to-P ratio circuit, the voltage across the resistor will be very **low.**

Summary of TC-to-P Ratios

The time constant-to-period ratio (TC-to-P) is the ratio of the pulse-duration time of the input pulse voltage to the time constant of the RL circuit.

So far, only the short and long TC-to-P ratios have been discussed. Fig. 6-43 shows the resistor and inductor waveshapes for the six TC-to-P ratios when a pulse voltage is applied to the RL circuit.

Notice that the inductor voltage will always have the sharp leading edge of the pulse input voltage, but the drop in inductor voltage from its maximum to minimum value will be in direct relationship to the time constant of the circuit, with respect to the period of the pulse.

With a short ratio the drop will be slow. The very short ratio produces a much more rapid decrease, while the extremely short ratio produces a spike waveshape or a very rapid decrease. The intermediate, long, and very long ratios prevent the inductor voltage from decreasing any appreciable amount. The very long ratio produces a waveshape across the inductor that is almost identical to the pulse input voltage.

Notice also that the resistor waveshapes will always have a gradual rise from minimum to maximum value. The very long ratio produces an almost negligible resistor voltage, the intermediate ratio produces a perfect sawtooth voltage waveform, while the extremely short ratio produces a resistor waveshape that is almost identical to the pulse input voltage.

If a mirror-image of the resistor voltage waveform is superimposed on the inductor voltage waveform, the result would be the input pulse shape.

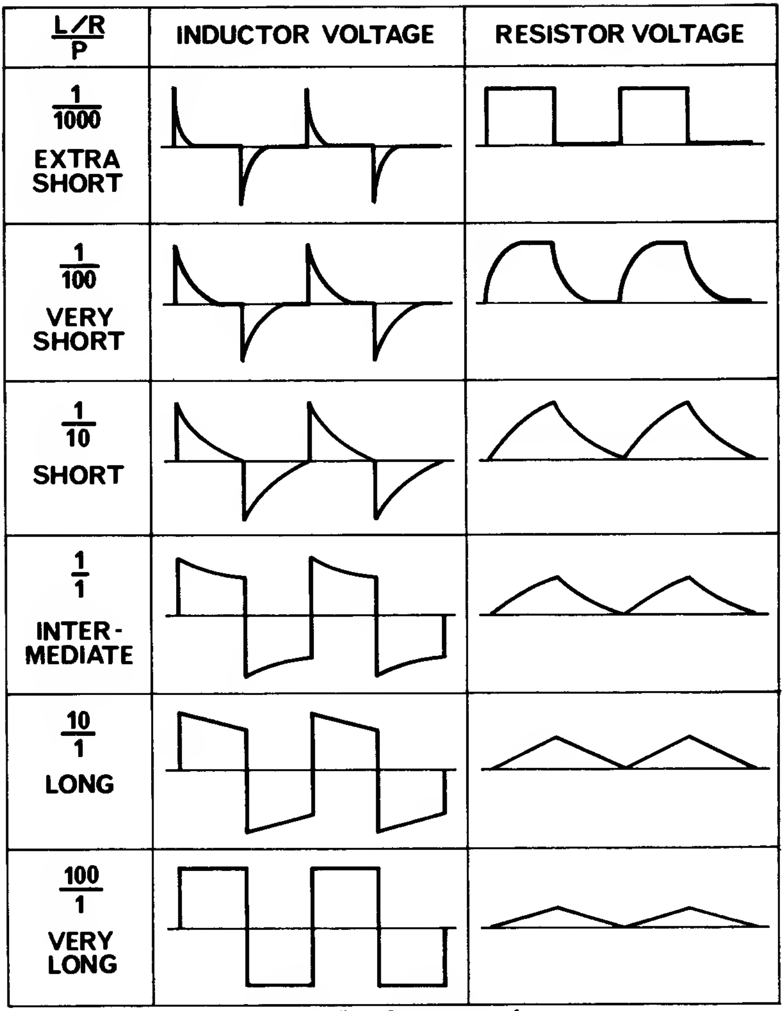


Fig. 6-43. RL voltage waveshapes.

Q6-49. When the input pulse voltage and the inductor voltage are almost identical, the TC-to-P ratio is ________ ________.

Q6-50. When inductor voltage is an extreme spike voltage, the TC-to-P ratio is ________ ________.

Q6-51. When resistor voltage is almost identical to the input pulse voltage, the TC-to-P ratio is ________ ________.

Your Answers Should Be:

A6-49. When the input pulse voltage and the inductor voltage are almost identical, the TC-to-P ratio is very **long.**

A6-50. When inductor voltage is an extreme spike voltage, the TC-to-P ratio is **extra short.**

A6-51. When resistor voltage is almost identical to the input pulse voltage, the TC-to-P ratio is **extra short.**

CAPACITANCE

Capacitance is the property of an electrical circuit that opposes a change in voltage. Capacitance has the same reaction to voltage that inductance has to current. That is, when the voltage applied across a circuit is increased or decreased, capacitance resists that change.

Construction of a Capacitor

A basic capacitor, sometimes called a condenser, is shown in Fig. 6-44. It consists of two conducting metallic plates separated by a layer of air or other insulating material such as glass, mica, or oil. The insulating material between the two conducting plates is called the *dielectric.*

All capacitors have two plates with an insulator separating them. In practice, these plates are often stacked or even rolled into a compact form, as shown in Fig. 6-45.

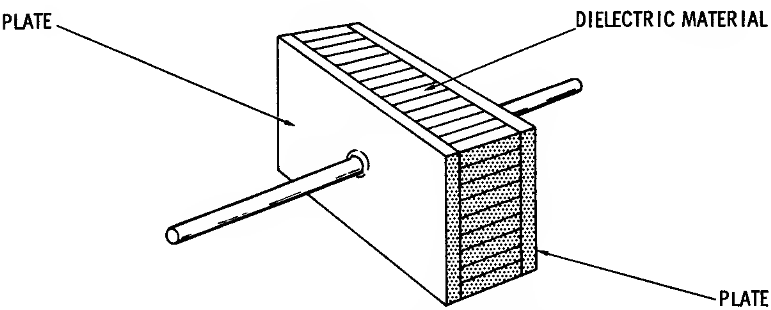


Fig. 6-44. Basic capacitor construction.

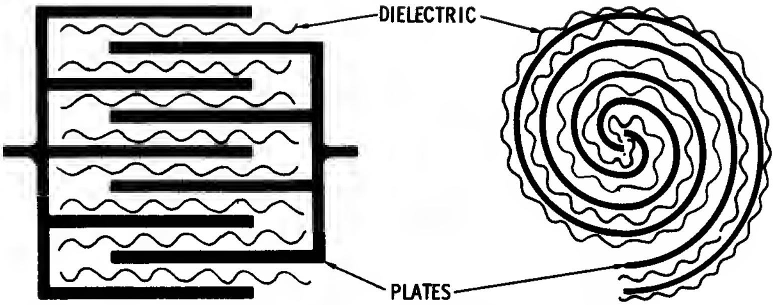


Fig. 6-45. Capacitor construction methods.

Symbols for a Capacitor

Capacitors can be classified into two categories—*fixed* or *variable*. Fig. 6-46 shows the schematic symbol for each category. The fixed capacitor, as its name implies, is made to have a definite value of capacitance, while the variable capacitor can be varied in value over a predetermined range.

The usual symbol, or alphabetical designation, used to identify capacitance is the letter *C*.

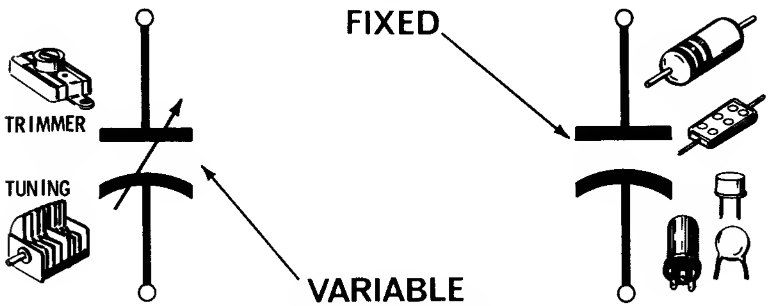


Fig. 6-46. Capacitor symbols.

Q6-52. The insulating material between the plates of a capacitor is called the ________.

Q6-53. The two types of capacitors are ________ and ________.

Q6-54. Capacitance is the property of an electrical circuit that opposes changes in ________.

Your Answers Should Be:

A6-52. The insulating material between the plates of a capacitor is called the **dielectric.**

A6-53. The two types of capacitors are **fixed** and **variable.**

A6-54. Capacitance is the property of an electrical circuit that opposes changes in **voltage.**

CAPACITANCE MEASUREMENTS

Each electrical component must have a standard against which its value can be measured. The unit of measurement for capacitance is the *farad.*

Capacitor Action in a D-C Circuit

When a capacitor is first connected to a battery, as shown in Fig. 6-47, electrons flow to the capacitor plate and remain there, since the opposite plate is separated from the first by the dielectric. The electrons from the opposite plate are attracted to the positive battery terminal. After this initial movement of electrons one plate is filled with all of the electrons that the battery can force into it, while the other plate loses the same number of electrons. One plate is negative, the other positive. No more electrons flow; the capacitor is *charged.* The voltage between the plates is equal and opposite to the battery voltage.

Capacitor Action in an A-C Circuit

Current cannot pass through a capacitor, but alternating current appears to do so. If the voltage across the plates is continuously varied, the number of electrons on the plates

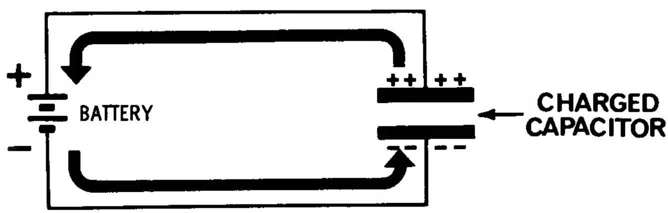


Fig. 6-47. Capacitor action in d-c circuit.

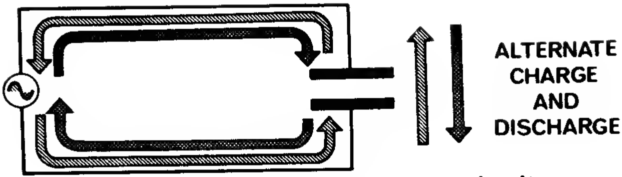


Fig. 6-48. Capacitor action in a-c circuit.

varies. As shown in Fig. 6-48, an a-c voltage can, in effect, get across the dielectric. Since the voltage is alternating, it causes an alternating current on the other side. Voltage changes are transmitted across the gap.

Unit of Measurement for Capacitors

Capacitance is measured in farads. Fig. 6-49 shows that the amount of capacitance in a capacitor is the quantity of electrical charges (in coulombs) that must be moved from one plate to the other in order to create a difference of 1 volt between the plates. The number of coulombs transferred is called the *charge*. One farad is the capacitance in which a charge of 1 coulomb produces a difference of 1 volt between the plates. The larger the capacitance of a capacitor, the more charge it will hold.

Capacitance values are usually specified in microfarads (millionths of a farad, abbreviated mfd or μf) or in picofarads (pf). Picofarads were formerly called micromicrofarads (mmf or $\mu\mu$f).

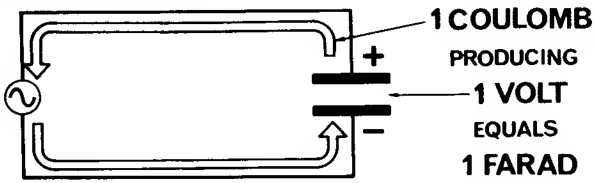


Fig. 6-49. Unit of measurement for capacitors.

Q6-55. The unit of measurement for capacitance is the ________.

Q6-56. Common units of measurement used for capacitors are ________ and ________.

Q6-57. When one plate of a capacitor has been filled with the maximum number of electrons, it is ________.

Your Answers Should Be:

A6-55. The unit of measurement for capacitance is the **farad.**

A5-56. Common units of measurement used for capacitors are **microfarads** and **picofarads.**

A6-57. When one plate of a capacitor has been filled with the maximum number of electrons, it is **charged.**

FACTORS AFFECTING CAPACITANCE VALUE

Plate Area

The amount of electrical charge that can be stored in a capacitor (the number of electrons that can be placed on the plate) varies with the area of the plate. Consequently, capacitance varies directly with area. When the area is doubled or twice as many plates are connected in parallel, there is twice as much area to store electrons, and the capacitance is therefore twice as great (Fig. 6-50).

Fig. 6-50. Plate area affects capacitance.

Distance Between Plates

Capacitance can also be increased by placing the plates closer together, as shown in Fig. 6-51. When the plates are closer, the attraction between the negative charges on one side and the positive charges on the other side is greater,

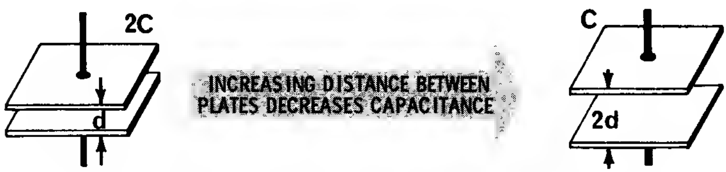


Fig. 6-51. Distance between plates affects capacitance.

and thus more charge can be stored. It is, of course, necessary to keep the plates far enough apart so that the charge does not jump the gap.

Changing Dielectric Material

Fig. 6-52 shows that higher values of capacitance can be obtained by using an insulating material (dielectric) other than air. Dielectrics such as mica, glass, oil, and *Mylar* are a few of the materials that can sustain a high electric stress

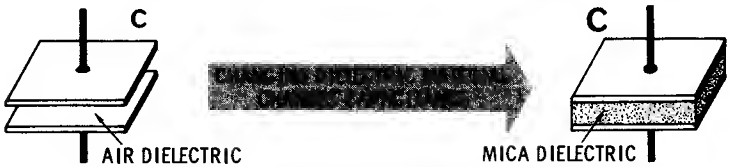


Fig. 6-52. Dielectric material affects capacitance.

without breaking down. This property is called *dielectric constant*. The higher the dielectric constant, the better the dielectric. Air has a dielectric constant of 1, glass about 5, and mica 2.5 to 6.6.

Besides allowing the plates to be placed closer together, a dielectric has another effect on capacitance. Dielectric material contains a large number of electrons and other carriers of electrical charge. Although electrons cannot flow as in a conductor, they are held rather loosely in the structure and can move slightly. The distortion of the structure of the dielectric, which is caused by charging the capacitor, has a large effect on the forces of attraction and repulsion that aid or oppose the flow of the electrons.

Q6-58. If the plate area of a capacitor is halved, the value of capacitance will be ________ its original value.

Q6-59. If the distance between the plates of a capacitor is doubled, the capacitance will be ________ its original value.

Q6-60. If mica is substituted for air as the dielectric, the capacitance will be ________.

Your Answers Should Be:

A6-58. If the plate area of a capacitor is halved, the value of capacitance will be **one-half** its original value.

A6-59. If the distance between the plates of a capacitor is doubled, the capacitance will be **one-half** its original value.

A6-60. If mica is substituted for air as the dielectric, the capacitance will be **higher.**

CAPACITORS IN COMBINATION

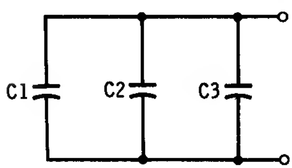
Capacitors, like resistors and inductors, are often connected in either series, parallel, or series-parallel in electronic circuits. Therefore, the rules that must be understood for combining resistors and inductors also apply to capacitors, but for capacitors they are just the opposite.

Capacitors in Parallel

As you have previously learned, resistors and inductors in series are added. Two resistors or inductors in series have the same effect as a single, larger resistor or inductor. Capacitors *add in parallel,* as shown in Fig. 6-53. It is easy to understand why this is true if you remember that the more plates, or the larger the plate area of a capacitor, the greater the capacitance. If two or more capacitors are connected in parallel, their total capacitance can be found by adding their values.

Capacitors in Series

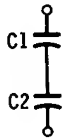
Capacitors connected in series can be analyzed the same way as resistors or inductors connected in parallel. Fig. 6-54



$$C_T = C1 + C2 + C3$$

Fig. 6-53. Parallel capacitor formula.

shows the two formulas that can be used to determine the total capacitance of the series-connected capacitors.



$$C_T = \frac{C1 \times C2}{C1 + C2} \text{ OR } \left\{ \text{IF EQUAL VALUES, } \frac{\text{VALUE OF ONE C}}{\text{NUMBER OF C's}} \right.$$

Fig. 6-54. Series capacitor formula.

Capacitors in Series-Parallel

When capacitors are connected in series-parallel, the same method used to determine equivalent resistance or inductance can be used. Fig. 6-55 shows an example of analyzing such a circuit. Remember, just reverse the resistor-inductor formulas when working with capacitors.

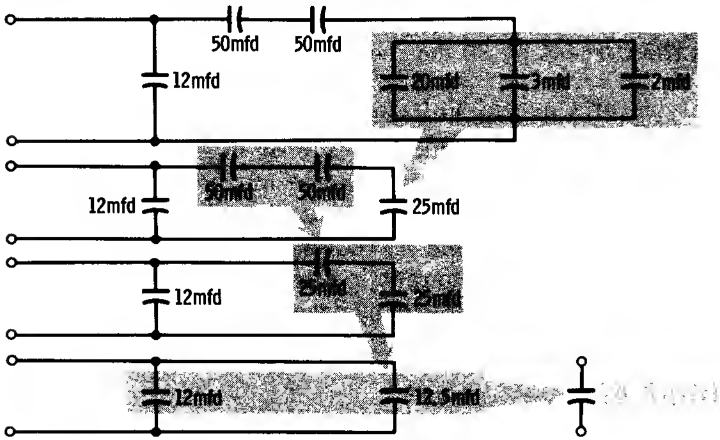


Fig. 6-55. Analysis of series-parallel circuit.

Q6-61. If three .02-mfd capacitors are connected in parallel, the total capacitance will be ________ mfd.

Q6-62. If two .05-mfd capacitors are connected in series, the total capacitance will be ________ mfd.

Q6-63. If a 25-mfd and a 100-mfd capacitor are connected in series, total capacitance will be ______ mfd.

Your Answers Should Be:

A6-61. If three .02-mfd capacitors are connected in parallel, total capacitance will be **.06** mfd.

A6-62. If two .05-mfd capacitors are connected in series, total capacitance will be **.025** mfd.

A6-63. If a 25-mfd and a 100-mfd capacitor are connected in series, total capacitance will be **20 mfd.**

CURRENT-VOLTAGE PHASE RELATIONSHIP IN A-C CAPACITIVE CIRCUITS

As with inductance, current and voltage are *not* in phase in a capacitive circuit. In a capacitive circuit, the voltage lags the current by 90 degrees.

Analysis of Current-Voltage Relationship

At any instant, the current into or out of a capacitor is proportional to the rate of change of the applied voltage. This can be seen in Fig. 6-56. The applied voltage is changing most rapidly at time A, the beginning of the sine-wave cycle; therefore, the current is at maximum. At time B the voltage across the capacitor has reached its peak and for the moment is not changing. Therefore, current at this instant

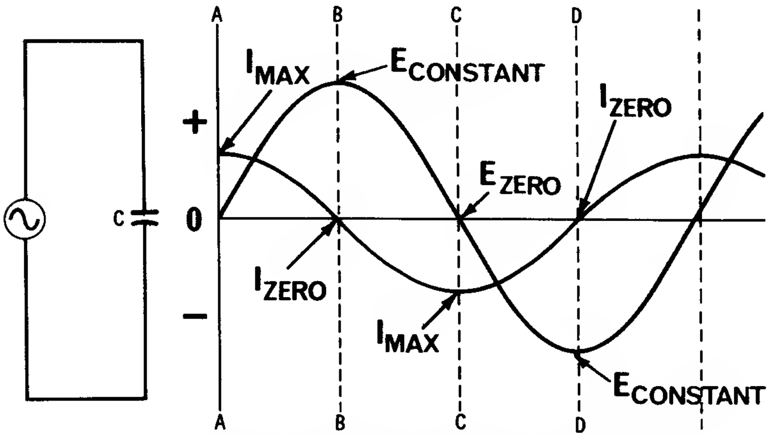


Fig. 6-56. Current-voltage relationship in capacitive circuit.

is zero. At time C, voltage across the capacitor again is changing quite rapidly (but in the negative direction), and so the current is at its negative peak. At time D, when the voltage reaches its negative peak and is momentarily not changing, the current waveform passes through zero once more.

If we trace the current from point to point along the voltage waveform, the result is a sine wave, but it is one that leads the voltage by exactly 90 degrees. This shows that if the voltage across the capacitor is a continuous sine wave with a constant amplitude, the current through the capacitor circuit is a sine wave that is 90 degrees ahead of the voltage.

Vector Analysis of Current-Voltage Relationship

Fig. 6-57 shows the vector representation of the current-voltage phase relationship in a capacitive circuit. The current vector leads the voltage vector by 90 degrees. A com-

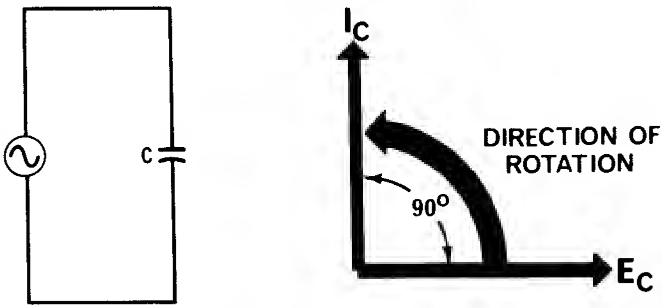


Fig. 6-57. Vector representation of current-voltage phase relationship.

parison of the vector and the current and voltage waveforms shown in Fig. 6-56 shows that at any instant of time, the voltage lags behind the current by 90 degrees.

Q6-64. In a capacitive circuit, current ________ voltage by 90 degrees.

Q6-65. The phase relationship between voltage and current is caused by ________ effects.

Q6-66. In a vector representation, the voltage vector is shown 90 degrees ________ the current vector.

Your Answers Should Be:

A6-64. In a capacitive circuit, current **leads** voltage by 90 degrees.

A6-65. The phase relationship between voltage and current is caused by **capacitive** effects.

A6-66. In a vector representation, the voltage vector is shown 90 degrees **behind** the current vector.

CAPACITIVE REACTANCE

Capacitance has a reactance or opposition to alternating current. Unlike inductance, the reactance of the capacitor decreases as the frequency of the alternating current increases.

Capacitive Reactance Formula

The symbol for capacitive reactance is X_C. The letter X is used to denote reactance and the C indicates that it is the reactance offered by a capacitor. The formula for capacitive reactance is shown in Fig. 6-58.

$$X_C = \frac{1}{2\pi f C}$$

(OHMS) (HERTZ) (FARADS)

Fig. 6-58. Capacitive reactance formula.

How Capacitive Reactance Operates

Because the circuit shown in Fig. 6-59 contains no resistance, the voltage across the capacitor will be the same value as the source voltage at every instant.

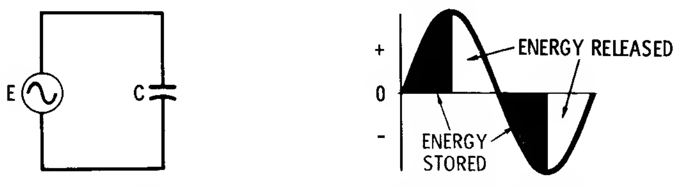


Fig. 6-59. Capacitive reactance in a-c circuits.

When a capacitor is charged up to a voltage E, it stores an amount of energy equal to the capacitance times the voltage. The capacitor will store a particular amount of energy every time the voltage reaches its positive or negative peaks. The energy depends only on capacitance and peak voltage. Fig. 6-60 shows that when the frequency of the power source is doubled and the peak voltage (E) is unchanged, the capacitor will charge every half-cycle to the same amount as before; but, it will have to do this twice as fast. This means that the same amount of energy must be supplied to the capacitor in only half the time. And since the voltage is the same, we must have twice the current to supply this same amount of total energy.

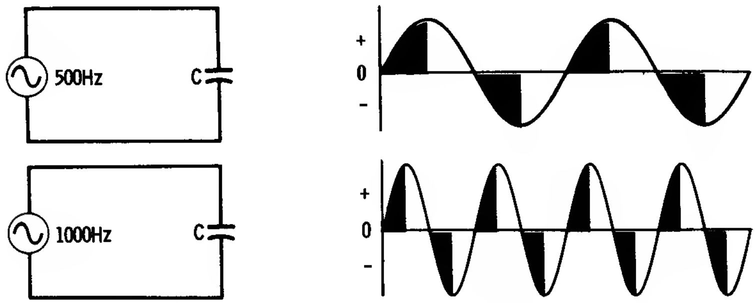


Fig. 6-60. Effect of frequency on capacitive reactance.

Capacitive reactance depends on frequency. Since it allows more current as frequency increases, capacitive reactance must decrease as the frequency increases.

Capacitive reactance also depends on the size of the capacitance. As capacitance increases, more current is needed to charge the capacitor to the same voltage (since the amount of energy stored equals C $\times$ E). As a result, capacitive reactance decreases when capacitance increases.

Q6-67. The symbol used to represent capacitive reactance in formulas is ________.

Q6-68. If the frequency of the voltage applied to a capacitor decreases, capacitive reactance ________.

Q6-69. If the capacitance of a capacitor is increased, its capacitive reactance ________.

Your Answers Should Be:

A6-67. The symbol used to represent capacitive reactance in formulas is X_C.

A6-68. If the frequency of the voltage applied to a capacitor decreases, capacitive reactance increases.

A6-69. If the capacitance of a capacitor is increased, its capacitive reactance decreases.

RESISTIVE-CAPACITIVE CIRCUITS

Since all circuits have some resistance, a pure capacitive circuit cannot exist. The leads of capacitors have some small value of capacitance. When the circuit contains both resistance and capacitance, the overall opposition to current is called impedance. The symbol is Z, as it was for impedance in an RL circuit.

Impedance Formula

As you already know, we cannot add resistance and capacitance because they are two different quantities (resistance is measured in ohms, capacitance in farads). Instead, it is necessary to use capacitive reactance, which was discussed previously. However, just as with inductance, to add resistance to capacitive reactance it must be remembered that resistive current is in phase with the voltage while capacitive current leads the voltage by 90 degrees. The two cannot be added directly—they must be added vectorially as shown

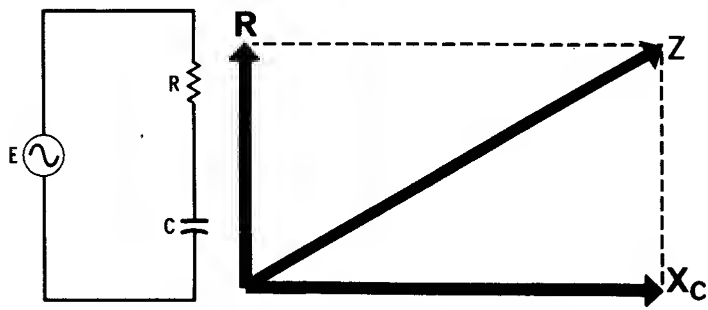


Fig. 6-61. Vector determination of impedance.

in Fig. 6-61. The capacitive-reactance vector is 90 degrees ahead of the resistance vector. The resulting quantity, an impedance, is somewhere between the two vectors and its length (quantity) is the diagonal of the reactangle they form. This is *capacitive impedance,* which is different from inductive impedance because it leads the resistance vector.

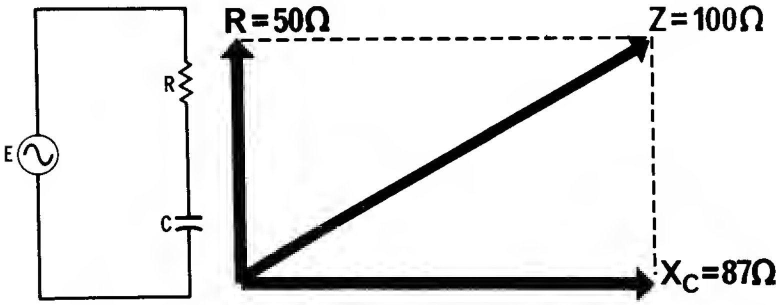


Fig. 6-62. Application of vectors to determine impedance.

Fig. 6-62 shows an example of the vector analysis of a circuit having a capacitive reactance of 87 ohms and a resistance of 50 ohms. Another formula that can be used to determine impedance of an RC circuit is shown in Fig. 6-63.

$$Z = \sqrt{R^2 + X_C^2}$$

IMPEDANCE (OHMS) = THE SQUARE ROOT OF RESISTANCE SQUARED PLUS CAPACITIVE REACTANCE SQUARED.

Fig. 6-63. Impedance formula.

Q6-70. The overall opposition to current in an RC circuit is ________.

Q6-71. An RC circuit with a resistance of 10 ohms and capacitive reactance of 10 ohms has an impedance of ________ ohms.

Q6-72. An RC circuit with a resistance of 50 ohms and a capacitive reactance of 87 ohms has an impedance of ________ ohms.

Your Answers Should Be:

A6-70. The overall opposition to current in an RC circuit is **impedance.**

A6-71. An RC circuit with a resistance of 10 ohms and capacitive reactance of 10 ohms has an impedance of **14.4** ohms.

A6-72. An RC circuit with a resistance of 50 ohms and a capacitive reactance of 87 ohms has an impedance of **100** ohms.

TIME CONSTANT IN RC CIRCUITS

Whenever a pulse voltage is applied to an RC circuit, the waveshape of the input pulse is distorted. The capacitive effects of the circuit, causing the current to lead the voltage, cause this distortion. The time constant of the RC circuit is the amount of time required for the circuit current to charge the capacitor to 63 percent of the applied voltage.

Time Constant Formula

The formula for determining the length of time for the capacitor charge to reach 63 percent of its maximum value is shown in Fig. 6-64. If values of R and C are in megohms or microfarads or picofarads (micromicrofarads), the formulas are given to simplify the process of division.

Fig. 6-65 shows several examples of how the time constant formula is used to determine the time constant of the RC circuit. Notice that as the values of C or R increase, the time constant of the RC circuit increases.

$$TC = R \times C$$

TIME CONSTANT (SECONDS)		RESISTANCE (OHMS)		CAPACITANCE (FARADS)
TC (SECONDS)	=	R (MEGOHMS)	x	C (MICROFARADS)
TC (μ SECONDS)	=	R (OHMS)	x	C (MICROFARADS)
TC (μ SECONDS)	=	R (MEGOHMS)	x	C (PICOFARADS)

Fig. 6-64. RC time constant formulas.

TC(sec) = R(megohms) x C(mfd)

TC(sec) = 2meg x 4mfd

TC(sec) = 8sec

TC(μsec) = R(ohms) x C(mfd)

TC(μsec) = 50Ω x 5mfd

TC(μsec) = 250μsec

Fig. 6-65. Application of RC time constant formula.

RC Waveforms

When a pulse of a given time duration is applied to an RC circuit, the circuit distorts the pulse voltage as explained earlier. Fig. 6-66 shows the waveshape's pulse input voltage, the capacitor voltage, and the resistor voltage. The voltage across the capacitor is called the *integrated voltage* and the voltage across the resistor is called the *differentiated voltage.*

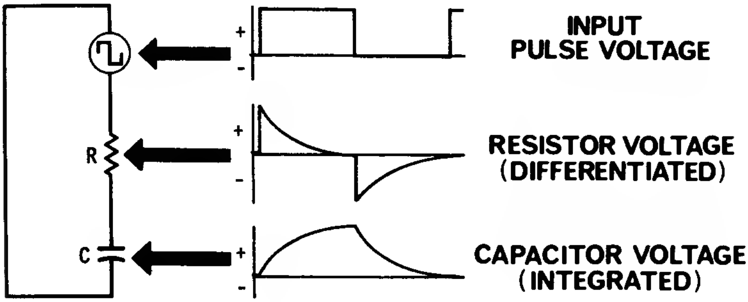


Fig. 6-66. RC waveforms.

Q6-73. The voltage across the capacitor in an RC circuit is called the ________ voltage.

Q6-74. A resistor of 10,000 ohms and a capacitor of .02 mfd would have a time constant of ________ microseconds.

Q6-75. The voltage across the resistor in an RC circuit is called the ________ voltage.

Your Answers Should Be:

A6-73. The voltage across the capacitor in an RC circuit is called the **integrated** voltage.

A6-74. A resistor of 10,000 ohms and a capacitor of .02 mfd would have a time constant of 200 microseconds.

A6-75. The voltage across the resistor in an RC circuit is called the **differentiated** voltage.

Current in RC Circuits

The current through the RC circuit, or the charge across the capacitor will reach 63 percent of its maximum value in one time constant. Fig. 6-67 shows that a total of *five* time constants are required for a capacitor charge to reach its maximum value. For this discussion, assume a total circuit current of 10 amperes and an applied pulse voltage of 100 volts as an example:

a. During the first time constant, the circuit current will decrease 63 percent of 10 amperes, to 3.7 amperes. The voltage across the capacitor will increase to 63 percent of the applied voltage or 63 volts. The resistor voltage will decrease 63 percent of the applied voltage or to 37 volts.
b. During the second time constant, the circuit current will decrease another 63 percent of the remaining value of 3.7 amperes, or an additional 2.3 amperes (3.7 − 2.3 = 1.4 amperes). The voltage across the capacitor will increase another 63 percent to 86 volts, and the resistor voltage will decrease to 14 volts.
c. During the third time constant, current will decrease another 63 percent to 0.5 amperes. Capacitor voltage increases to 95 volts, and resistor voltage drops to 5 volts.
d. The circuit current continues to decrease 63 percent of the remaining value during the fourth and fifth time constants, until at the end of the fifth time constant, circuit current is at zero, capacitor voltage is 100 volts, and resistor voltage is zero.

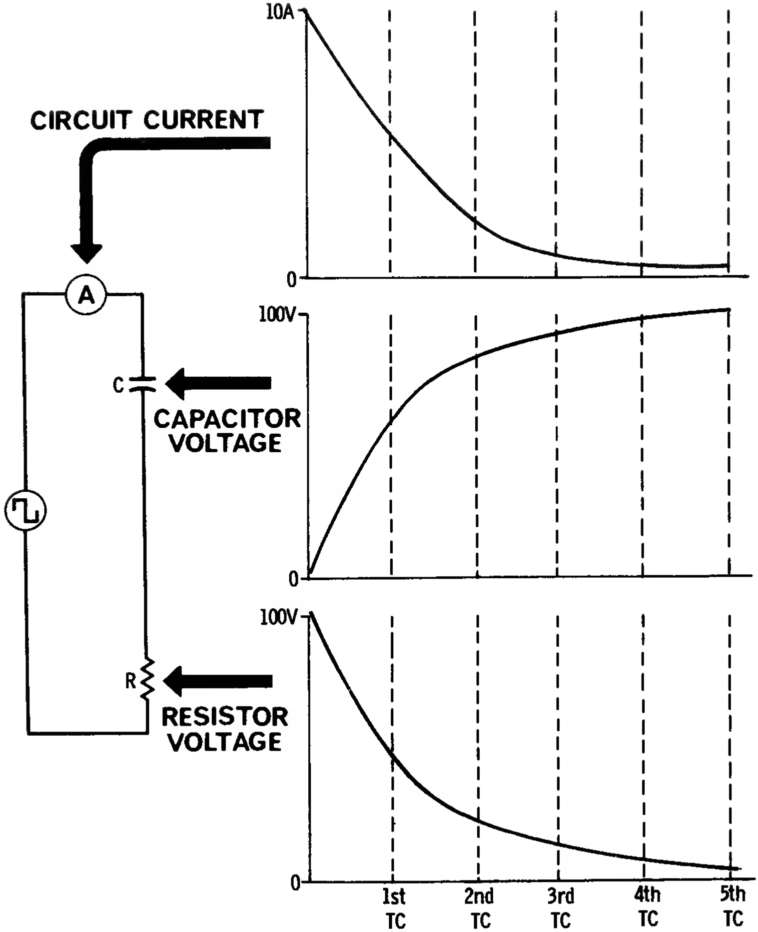


Fig. 6-67. Analysis of RC circuit current.

Q6-76. A capacitor in an RC circuit will charge to its maximum voltage in ________ time constants.

Q6-77. The resistor voltage in an RC circuit will drop 95 percent by the end of the ________ time constant.

Q6-78. If 20 volts are applied to an RC circuit, capacitor voltage will be ________ volts after the fourth time constant.

Your Answers Should Be:

A6-76. A capacitor in an RC circuit will charge to its maximum voltage in **five** time constants.

A6-77. The resistor voltage in an RC circuit will drop 95 percent by the end of the **third** time constant.

A6-78. If 20 volts are applied to an RC circuit, capacitor voltage will be **19.6** volts after the fourth time constant.

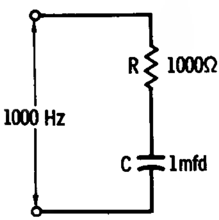
TIME CONSTANT-TO-PERIOD RATIO IN RC CIRCUITS

The time constant-to-period ratio (TC-to-P) for RC circuits is basically the same as for RL circuits except that the voltage waveform of the capacitor in the RC circuit is the same as the resistor waveform in the RL circuit, and the resistor voltage waveform in the RC circuit is the same as the inductor voltage waveform in the RL circuit.

TC-to-P Formula

It can be seen from Fig. 6-68 that the formula for determining the TC-to-P ratio is exactly the same as that for RL circuits. That is, the relationship between the time constant of the RC circuit and the period of the pulse voltage is obtained by dividing the time constant by the period. It must be remembered that the time constant of an RC circuit is obtained by multiplying the value of C by the value of R as previously explained.

$$\frac{TC}{P}\ \frac{\text{(TIME CONSTANT)}}{\text{(PERIOD)}} = \frac{R \times C}{P}$$



$$TC = R \times C = 1000\Omega \times 1\text{mfd} = .001\text{sec}$$

$$P = \frac{1}{\text{FREQ.}} = \frac{1}{1000} = .001\text{sec}$$

$$\frac{TC}{P} = \frac{.001}{.001} = \frac{1}{1}$$

Fig. 6-68. RC circuit TC-to-P formula.

The ratio of time constant to period is generally expressed in six general categories, as shown in Fig. 6-69. A comparison of these six categories with those given for RL circuits shows that the relationships of TC-to-P are the same.

$$\frac{1}{1000} = \text{EXTRA SHORT}$$

$$\frac{1}{100} = \text{VERY SHORT}$$

$$\frac{1}{10} = \text{SHORT}$$

$$\frac{1}{1} = \text{INTERMEDIATE}$$

$$\frac{10}{1} = \text{LONG}$$

$$\frac{100}{1} = \text{VERY LONG}$$

Fig. 6-69. RC circuit TC-to-P categories.

Q6-79. A time constant-to-period ratio of 1 to 100 is classified as ________.

Q6-80. A long TC-to-P ratio would be one with a ratio of ________ to ________.

Q6-81. A time constant-to-period ratio of 1 to 1 is classified as ________.

Your Answers Should Be:

A6-79. A time constant-to-period ratio of 1 to 100 is classified as ***very short.***

A6-80. A long TC-to-P ratio would be one with a ratio of **10 to 1.**

A6-81. A time constant-to-period ratio of 1 to 1 is classified as **intermediate.**

RC Circuit and Short TC-to-P Ratio

When the time constant of the RC circuit is short in respect to the period of the pulse, the following actions shown in Fig. 6-70 takes place:

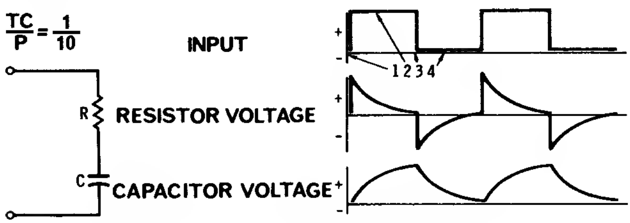


Fig. 6-70. Waveforms for short TC-to-P RC circuit.

1. As the pulse input voltage increases from minimum to maximum, the entire input voltage is across the resistor due to the low reactance of the capacitor.
2. During the long time (in respect to the TC) that the input pulse remains at its maximum value, the circuit current can charge the capacitor to the peak value of the input voltage, causing the resistor voltage to drop to its minimum value.
3. As the input pulse voltage drops to minimum, the charged capacitor (charged to the input pulse value) rapidly starts to discharge through the resistor, causing resistor voltage to be at its maximum negative value.
4. As the capacitor continues to discharge during the minimum value pulse time, capacitor voltage will drop from maximum to minimum and resistor voltage will drop from maximum negative to zero.

RC Circuit and Long TC-to-P Ratio

When the time constant of the RC circuit is long in respect to the period of the pulse, the following actions, as shown in Fig. 6-71, take place:

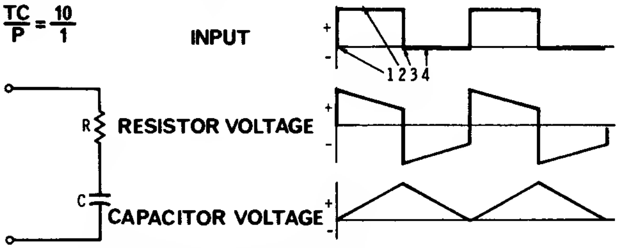


Fig. 6-71. Waveforms for long TC-to-P RC circuit.

1. As the input voltage increases from minimum to maximum, the entire voltage is across the resistor due to the low impedance of the uncharged capacitor.
2. During the short time (in respect to the TC) that the input pulse remains at its maximum value, the charge across the capacitor cannot increase to its maximum value, therefore capacitor voltage will increase only slightly, and resistor voltage will drop only slightly.
3. As the input voltage drops to minimum, the capacitor (charged to a portion of the input voltage) rapidly starts discharging through the resistor, causing resistor voltage to be at its maximum negative value.
4. The capacitor will discharge to zero during the short time of minimum pulse voltage since capacitor charge and discharge time are identical. Resistor voltage will drop from maximum negative to zero.

Q6-82. During the time that input voltage increases from minimum to maximum, the entire voltage is across the ________.

Q6-83. When input voltage changes suddenly from maximum to minimum the capacitor will ______.

Q6-84. The capacitor of the RC circuit will charge to only a small portion of the input voltage with a ________ TC-to-P ratio.

> **Your Answers Should Be:**
>
> **A6-82.** During the time that input voltage increases from minimum to maximum, the entire voltage is across the **resistor.**
>
> **A6-83.** When input voltage changes suddenly from maximum to minimum the capacitor will **discharge.**
>
> **A6-84.** The capacitor of the RC circuit will charge to only a small portion of the input voltage with a **long** TC-to-P ratio.

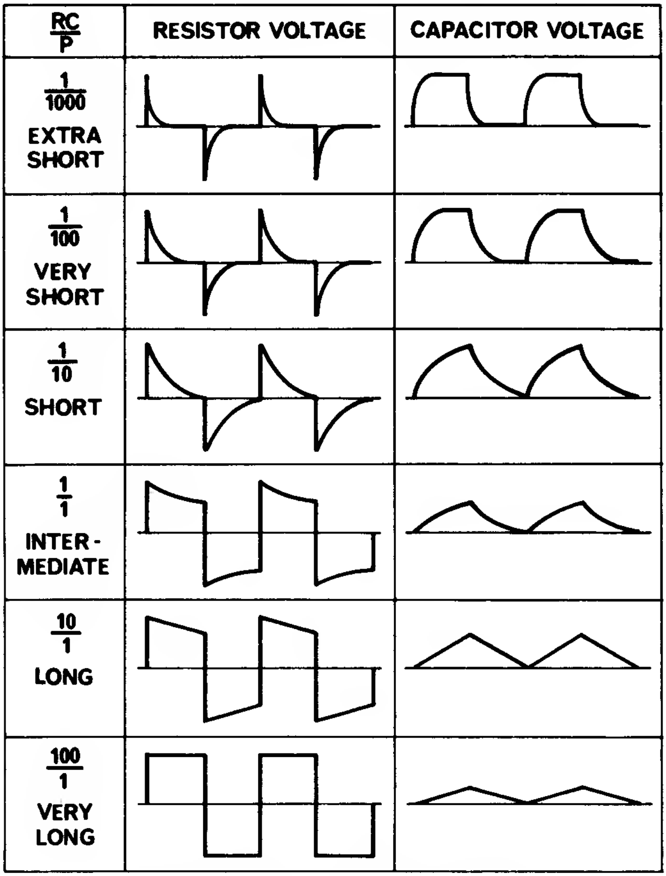


Fig. 6-72. RC circuit voltage waveforms.

Summary of TC-to-P Ratios

Only the short and long TC-to-P ratios have been discussed. Fig. 6-72 shows the resistor and capacitor waveshapes for the six TC-to-P ratios when a pulse voltage is applied to the RC circuit.

Notice that the resistor voltage will always have the sharp leading edge of the input pulse voltage, but the drop in resistor voltage from its maximum to minimum voltage value will be in direct relationship to the time constant of the circuit in respect to the period of the pulse. With an extremely short TC-to-P ratio, the drop in resistor voltage will be extremely rapid, while the very long ratio will produce a waveform across the resistor that is almost identical to the input pulse waveshape.

The capacitor voltage waveforms are the opposite of the resistor waveforms. The extremely short ratio will produce a capacitor waveform that is almost identical to the input pulse waveshape, while the very long ratio produces a waveshape across the capacitor that is a sawtooth voltage of very small amplitude. Notice also that the capacitor waveshapes will always have a gradual rise from minimum to maximum and then back to minimum.

Q6-85. When the input pulse voltage and the capacitor voltage are almost identical, the TC-to-P ratio is ________ ________.

Q6-86. When resistor voltage is an extreme spike voltage, the TC-to-P ratio is ________ ________.

Q6-87. When the resistor voltage is almost identical to the input pulse voltage, the TC-to-P ratio is ________ ________.

Your Answers Should Be:

A6-85. When the input pulse voltage and the capacitor voltage are almost identical, the TC-to-P ratio is **extremely short.**

A6-86. When resistor voltage is an extreme spike voltage, the TC-to-P ratio is **extremely short.**

A6-87. When the resistor voltage is almost identical to the input pulse voltage, the TC-to-P ratio is **very long.**

SERIES LCR CIRCUITS

When a circuit contains both inductance and capacitance in addition to resistance, the rules that apply for both inductive and capacitive circuits must apply; however, the predominant reactance, either inductive or capacitive, will determine the overall circuit characteristics.

Vector Analysis of Series LCR Circuit

When vectors, shown in Fig. 6-73, are used to represent impedance, X_C or capacitive reactance is always drawn downward (negative reactance), while X_L or inductive reactance is drawn upward (positive reactance). This vector representation shows that inductive reactance and capacitive reactance provide opposite effects.

The two reactances in series cannot be added arithmetically. X_L and X_C tend to offset each other, therefore the total effect is the difference between the two. Fig. 6-74 shows

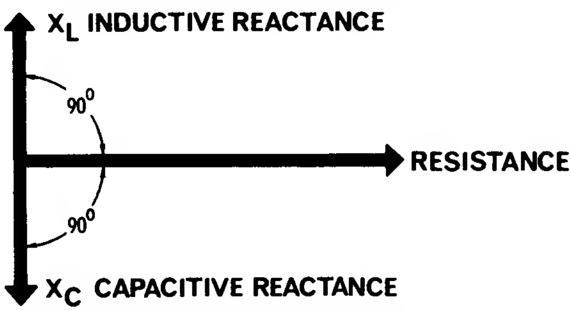


Fig. 6-73. Series LCR circuit impedance vectors.

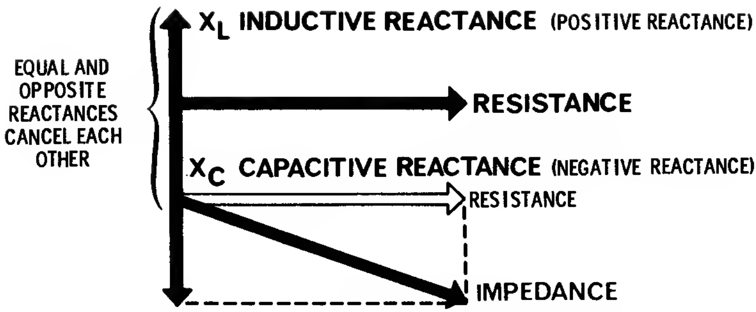


Fig. 6-74. Application of vectors to series LCR circuit.

that a circuit containing resistance, inductance, and capacitance will assume the characteristics of the predominant reactance.

LCR Circuit Impedance Formula

Fig. 6-75 shows the formula for determining the total impedance of a circuit containing X_L, X_C, and resistance. The formula can be modified to subtract the smaller reactance from the larger. The formula therefore can be $X_L - X_C$ or $X_C - X_L$ depending on which is the greater of the two reactances.

$$\underset{\text{IMPEDANCE (ohms)}}{Z} = \sqrt{R^2 + (X_L - X_C)^2}$$

Fig. 6-75. Impedance formula for LCR circuit.

Q6-88. **Inductive reactance (X_L) is a ________ reactance, while capacitive reactance is a ________ reactance.**

Q6-89. **A circuit with an inductive reactance of 100 ohms and a capacitive reactance of 25 ohms has a total reactance of ________ ohms.**

Q6-90. **The inductive vector is always drawn ________ and the capacitive vector is drawn ________.**

Your Answers Should Be:

A6-88. Inductive reactance (X_L) is a **positive** reactance, while capacitive reactance is a **negative** reactance.

A6-89. A circuit with an inductive reactance of 100 ohms and a capacitive reactance of 25 ohms has a total reactance of 75 ohms.

A6-90. The inductive vector is always drawn **upward** and the capacitive vector is drawn **downward.**

SERIES RESONANT CIRCUITS

Every combination of inductance and capacitance will have a *resonant frequency;* that is, one frequency at which the values of inductive reactance and capacitive reactance will equal each other. Because these reactances are equal but opposite to each other, they will cancel each other.

Analysis of Resonant LCR Circuit

A special case arises when the capacitive reactance and the inductive reactance are equal. Fig. 6-76 shows that as frequency increases, X_C decreases; it also shows that as frequency increases, X_L increases. At the point where X_L and X_C cross, or equal each other, the resonant frequency of that LC combination has been reached.

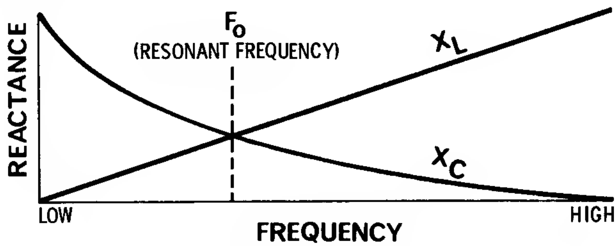


Fig. 6-76. Inductive-capacitive reactance curve.

Fig. 6-77 shows impedance and current plotted against frequency. Notice that both below and above the resonant frequency, impedance is high; consequently, the circuit current is low. Below the resonant frequency, the circuit acts

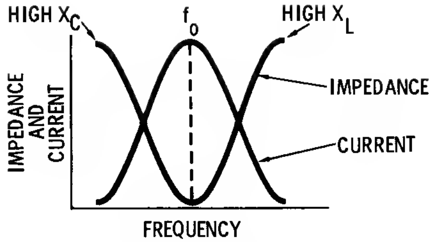
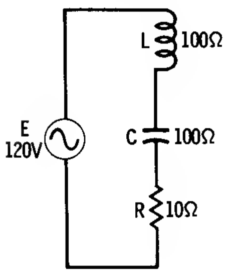


Fig. 6-77. Series LCR impedance-current curve.

capacitively and above the resonant frequency the circuit acts inductively. At the resonant frequency, however, impedance is at its minimum value; consequently, circuit current will be at its maximum value.

At the resonant frequency the voltage across both the inductor and capacitor can exceed the applied voltage. Because X_L and X_C counteract each other, resistance is the only opposition to circuit current, therefore current is high. However, the voltage across both L and C are a function of current times reactance (IX). Fig. 6-78 shows that the current times the inductive reactance (IX_L) and current times the capacitive reactance (IX_C) drops can exceed E applied.



1. AT RESONANCE X_L EQUALS X_C, CANCELING EACH OTHER.
2. CIRCUIT CURRENT IS DETERMINED BY E APPLIED AND R.
   $I = \frac{E}{R} = \frac{120}{10} = 12$ AMPS.
3. CURRENT THROUGH BOTH L AND C IS 12 AMPS.
4. E ACROSS BOTH L AND C IS DETERMINED BY $I \times X_L$ AND $I \times X_C$.
   $E = I \times X_L = 12 \times 100 = 1200V$

Fig. 6-78. Series LCR resonant circuit characteristics.

Q6-91. When the value of X_L equals X_C in a series LCR circuit, a condition called ________ occurs.

Q6-92. At the resonant frequency, circuit current is at its ________ value; impedance is at its ________ value.

Q6-93. Below the resonant frequency a series LCR circuit acts ________; above the resonant frequency, ________.

Your Answers Should Be:

A6-91. When the value of X_L equals X_C in a series LCR circuit, a condition called **resonance** occurs.

A6-92. At the resonant frequency, circuit current is at its **maximum** value; impedance is at its **minimum** value.

A6-93. Below the resonant frequency a series LCR circuit acts **capacitively**; above the resonant frequency, **inductively**.

Resonant Frequency Formula

Every combination of inductance and capacitance will have a resonant frequency. Fig. 6-79 shows the formula used

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

RESONANT FREQUENCY (HERTZ)

Fig. 6-79. Resonant-frequency formula.

to determine this resonant frequency. Notice that the values of L and C must be known in order to determine the frequency.

Power in Series LCR Circuits

No power is consumed in a purely inductive or capacitive circuit. In a series LCR circuit the only power consumed will be resistive power. Fig. 6-80 shows the relationship between inductive, capacitive, and resistive voltage, current, and power. Current I, which is in phase with the applied a-c voltage, flows through all three components, L, C, and R. During the first quarter-cycle of each sine wave, the inductance is returning energy to the circuit and the capacitance is taking energy from the circuit at the same rate. During the second quarter-cycle, the situation is reversed—the capacitor is returning energy, and the inductor is taking it out. This sequence occurs during each cycle.

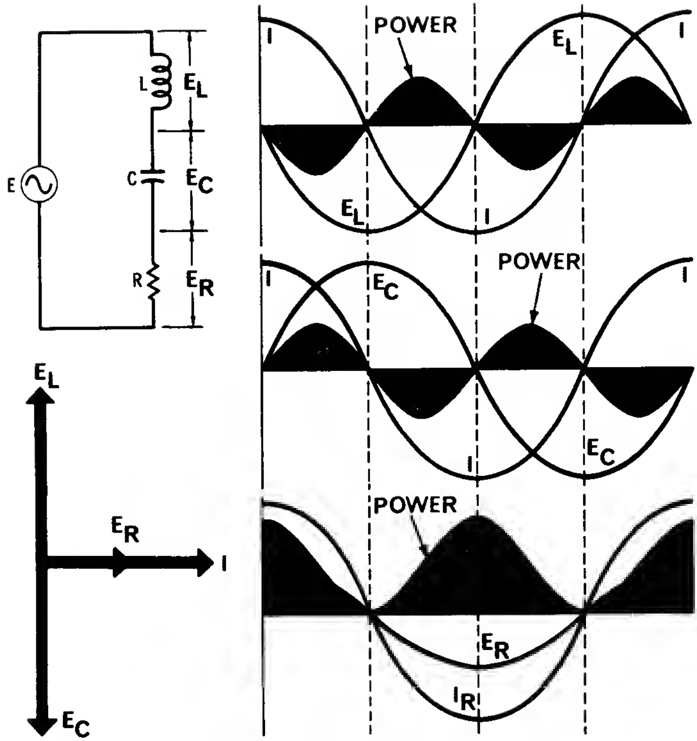


Fig. 6-80. Power in series LCR circuits.

The voltage across the capacitance is equal and opposite to the voltage across the coil at all times, and the two cancel. One voltage (E_C) is 90 degrees behind the current and the other voltage (E_L) is 90 degrees ahead.

Q6-94. The resonant frequency of a series LCR circuit containing a 2H inductor, 2-mfd capacitor, and a 100-ohm resistor is ________ Hz.

Q6-95. The power dissipated by a series resonant LCR circuit with an applied voltage of 120V, 1000 ohms X_L, 1000 ohms X_C, and 100 ohms R is ________watts.

Q6-96. In a series LCR resonant circuit inductive voltage and capacitive voltage are ________ degrees out of phase.

Your Answers Should Be:

A6-94. The resonant frequency of a series LCR circuit containing a 2H inductor, 2-mfd capacitor, and 100-ohm resistor is **79.5 Hz.**

A6-95. The power dissipated by a series resonant LCR circuit with an applied voltage of 120V, 1000 ohms X_L, 1000 ohms X_C, and 100 ohms R is **144** watts.

A6-96. In a series LCR resonant circuit inductive voltage and capacitive voltage are **180** degrees out of phase.

Q of a Series LCR Circuit

The *Q or quality* of a series resonant LCR circuit is the ratio of either X_L or X_C to resistance in the circuit. Either X_L or X_C can be used at resonance because both will be the same value. At frequencies below resonance, Q is the ratio of X_C to R, and above resonance, Q is the ratio of X_L to R. Fig. 6-81 shows the formulas for determining the Q of a series LCR circuit.

$$\text{“Q”} \quad \frac{X_L}{R} = \frac{1000\Omega}{10\Omega} = \frac{100}{1} \text{ (HIGH “Q”)}$$

$$\text{“Q”} \quad \frac{X_C}{R} = \frac{1000\Omega}{100\Omega} = \frac{10}{1} \text{ (LOW “Q”)}$$

Fig 6-81. Series LCR circuit Q formulas.

It can be seen that the value of R in series with L and C will determine the Q of the circuit. If the value of R is low, the ratio of R to X_L (or X_C) will be high, or the Q of the circuit will be high. If on the other hand the value of R is high, the Q of the circuit will be low. Fig. 6-82 shows that it is the value of resistance that determines the total circuit current at resonance. At frequencies either below or above resonance, circuit current is determined by the reactance of either inductor or capacitor, and the resistor.

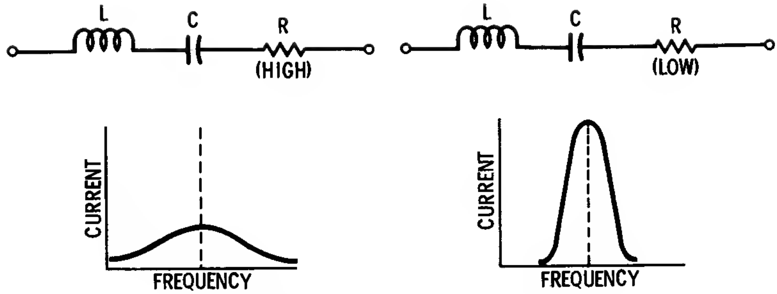


Fig. 6-82. Effect of resistance on circuit Q.

Therefore, the value of resistance will determine the amount of current primarily at the resonant frequency, and current will drop gradually on either side of the resonant frequency.

Series LCR circuits are normally given three broad Q ratings as shown in Fig. 6-83. A low-Q circuit, with a high value of resistance, will have low current and a very broad slope from minimum to maximum current. The medium-Q circuit has a higher current and a more rapid drop from minimum to maximum current. The high-Q circuit has a large resonant current and a very sharp drop on either side of resonance.

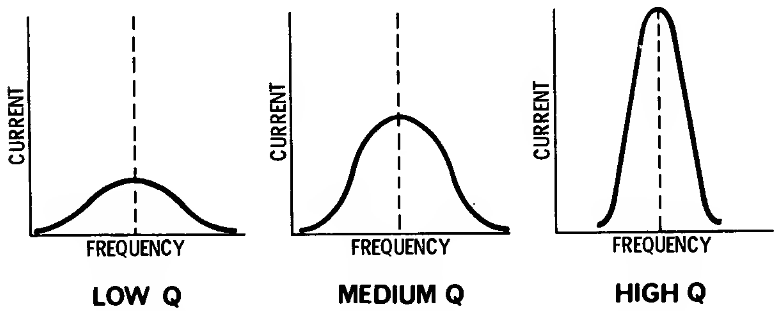


Fig. 6-83. Low-, medium-, and high-Q response curves.

Q6-97. An LCR circuit with an inductance of 0.5 henry a resistance of 10 ohms, and resonant at 1 kHz will have a Q of ________.

Q6-98. A series LCR resonant circuit with a very high current is called a ________-Q circuit.

Q6-99. Q is a ratio of inductive or capacitive reactance to ________.

Your Answers Should Be:

A6-97. An LCR circuit with an inductance of 0.5 henry a resistance of 10 ohms, and resonant at 1 kHz will have a Q of **314.**

A6-98. A series LCR resonant circuit with a very high current is called a **high-Q** circuit.

A6-99. Q is a ratio of inductive or capacitive reactance to **resistance.**

PARALLEL LCR CIRCUITS

The parallel LCR circuit consists of a capacitor in parallel with a resistor-inductor combination. In many instances, the resistance shown is not a physical resistor, but represents the d-c resistance of the inductor.

Analysis of a Parallel LCR Circuit

When an a-c voltage is applied to a parallel LCR circuit, each of the two branches shows reactance. As shown in Fig. 6-84, the capacitive reactance in the capacitor branch is high at low frequencies, and decreases as the frequency increases. Similarly, the inductive reactance of the inductor branch is low at low frequencies, and increases with the frequency.

The capacitor has a high reactance and the inductor a low reactance at frequencies below resonance. Consequently, most of the current is through the inductive branch and lags the applied voltage. Similarly, if the frequency is above resonance, most of the current is in the capacitive branch and will lead the applied voltage.

At some particular frequency the two reactances in a parallel resonant circuit are exactly equal. Since there is an a-c voltage applied across each branch, two kinds of current are present—an inductive current in the inductive branch and a capacitive current in the capacitive branch. At resonance the two currents are equal. But, because one of the currents leads the applied voltage by 90 degrees and the other lags the voltage by 90 degrees, the two currents are 180 degrees out of phase with each other. This means that they will cancel (add up to zero).

The applied voltage was kept constant as the frequency was varied. Since current is a minimum throughout the circuit at resonance, a parallel circuit has a higher impedance at its resonant frequency than at any other frequency.

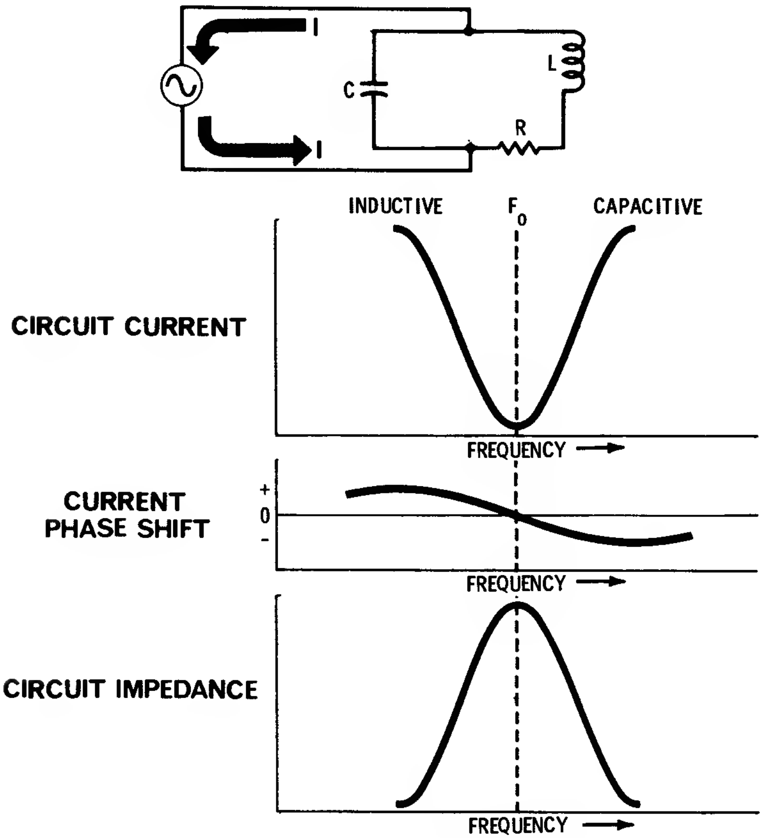


Fig. 6-84. Parallel LCR circuit analysis.

Q6-100. A parallel LCR circuit at a low frequency will act ________.

Q6-101. The impedance of a parallel LCR circuit at the resonant frequency is ________.

Q6-102. The circuit current of a parallel LCR circuit at the resonant frequency is ________ ________.

Your Answers Should Be:

A6-100. A parallel LCR circuit at a low frequency will act **inductively.**

A6-101. The impedance of a parallel LCR circuit at the resonant frequency is **high.**

A6-102. The circuit current of a parallel LCR circuit at the resonant frequency is **very low.**

Action Within the Parallel LCR Loop

The action within the parallel LCR circuit or loop formed by L and C will be just the opposite of the external circuit. Fig. 6-85 shows that the two large currents, inductive and capacitive, still exist, but only inside the loop. Energy alternately flows from capacitor to inductor and back again,

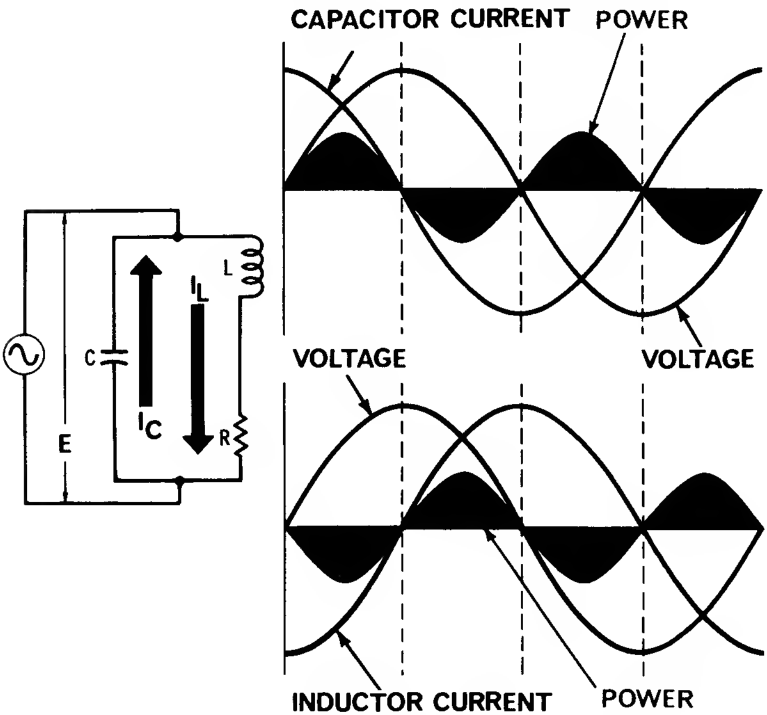


Fig. 6-85. Parallel LCR loop circuit analysis.

twice each cycle. The capacitor alternately charges and discharges, first in one direction and then in the other. The inductive magnetic field alternately builds up and collapses, changing polarity twice each cycle. But all this flow back and forth is contained in the loop, and none appears in the external circuit. The outside circuit only has to replenish the energy lost in any resistance the inductor has, and this constitutes the entire external current.

The Q of the circuit, just as in the series resonant circuit, is the inductive reactance at resonance divided by the resistance of the inductor $\left(\frac{X_L}{R_L}\right)$. In a parallel-resonant circuit the loop current between inductor and capacitor is Q times the external (resistive) current.

Impedance Formula for Parallel LCR Circuits

Fig. 6-86 shows the formula that can be used to determine the total impedance of parallel LCR circuits. It can be seen from the formula that the total circuit impedance will grow as X_L or X_C becomes greater relative to resistance. Impedance will decrease as R increases and draws more current.

$$Z_O = \frac{X_L \times X_C}{R}$$

(IMPEDANCE)

Fig. 6-86. Parallel LCR impedance formula.

Q6-103. In the parallel LCR circuit the loop current at resonance is ________.

Q6-104. The total impedance of a parallel LCR circuit at resonance with a 1-henry inductor, a 1-mfd capacitor and a d-c resistance of 1 ohm is ________.

Q6-105. The impedance in the loop or parallel LCR circuit at resonance is ________ ________.

Your Answers Should Be:

A6-103. In the parallel LCR circuit the loop current at resonance is **high.**

A6-104. The total impedance of a parallel LCR circuit at resonance with a 1-henry inductor, a 1-mfd capacitor and a d-c resistance of 1 ohm is **1 megohm.**

A6-105. The impedance in the loop or parallel LCR circuit at resonance is very **low.**

SUMMARY QUESTIONS

1. When there is current through a conductor, a magnetic field expands around the conductor. This field produces a counter emf as the current changes direction. The applied voltage and the counter emf are 180 degrees out of phase with each other. The current lags the applied voltage by 90 degrees, but leads the counter emf by 90 degrees.
   a. The counter emf is generated by an expanding ______ ______.
   b. The counter emf ______ the circuit current by ______ degrees.
2. Inductance opposes any change in current. The unit of measurement of inductance is the henry. Because the henry is an extremely large value of inductance, it is seldom found in electronic circuits. More common values are millihenrys and microhenrys.
   a. A millihenry is ______ of a henry.
   b. The unit of measurement for inductance is the ______.
3. The three factors that determine the amount of inductance of a coil are the number of turns, coil diameter, and core material. Increasing the number of turns or the coil diameter will increase inductance, and changing core material from air to either iron or powdered iron will increase inductance.
   a. If a coil with 50 turns has an inductance of 200 millihenrys, a decrease to 25 turns will lower the inductance to ______ millihenrys.

b. If a coil with a diameter of .5 inch and an inductance of 1000 millihenrys were doubled in diameter, inductance would increase to ________ millihenrys.

4. An a-c circuit containing only inductance will have a phase difference between the applied voltage and the circuit current of 90 degrees, with current lagging the voltage. This phase difference can be shown simply by the use of vectors.

   a. In an inductive circuit, the voltage ________ the current by ________ degrees.

   b. When using vectors, the length of each vector represents ________.

5. When inductors are connected in series, the total value of inductance is determined by adding the values of the individual inductors. When inductors are connected in parallel, either the *like* method, used for equal value inductors, or the *product-over-sum* method is used to determine total inductance. Total inductance of series-parallel connected inductors is determined by finding the inductance of the series and parallel branches. The same methods used to determine total resistance apply to finding total inductance.

   a. If two inductors connected in series have a total inductance of 650 millihenry, when L1 is 250 millihenrys, L2 inductance is ________ millihenrys.

   b. If total inductance is lower than the inductor with the lowest value, they are connected in ________.

6. Inductive reactance, represented by X_L is the opposition offered to alternating current by an inductor. X_L is measured in ohms. Inductive reactance differs from resistance in that when the frequency of the applied a-c voltage changes, the X_L changes. The lower the frequency, the lower the X_L; the higher the frequency, the higher the X_L.

   a. The amount of X_L of an inductor is dependent on the frequency of the applied a-c voltage and ________.

   b. Inductive reactance is measured in ________.

7. Inductors are frequently used in circuits called filters, which allow only certain frequencies to pass through them and block all others. The names of the various filter circuits describe their actions. The low-pass filter

passes only low frequencies and blocks high frequencies. The high-pass filter has the opposite effect. The band-pass filter passes only a band of frequencies and blocks frequencies on both sides of that band.

a. In a low-pass filter circuit, the inductance is in ____________ with the input-output terminals.

b. In a high-pass filter circuit, the inductance is in __________ with the input-output terminals.

8. A transformer is a device that consists of a primary and secondary winding and is used to transfer power from one voltage-current level to another voltage-current level. The three general classes of transformers are air core, iron core, and powdered iron core. When power is transferred from primary to secondary, the frequency of the a-c voltage remains the same, but the secondary voltage and current are 180 degrees out of phase with primary voltage and current. The amount of voltage and current in the secondary is determined by the turns ratio between the transformer primary and secondary. A step-up transformer will have a higher secondary voltage and lower secondary current, the amount being determined by the turns ratio. A step-down transformer will be just the opposite; a lower secondary voltage and higher secondary current, with the amount determined by the turns ratio.

   a. Transformer secondary current will be greater than primary current in a step-__________ transformer.

   b. Transformer secondary voltage will be greater than primary voltage in a step-__________ transformer.

   c. A transformer with five turns on the secondary for every primary turn and with 120 volts applied, will have a secondary voltage of __________ volts.

9. When an a-c circuit contains both inductance and resistance, the total opposition to alternating current is called impedance. Impedance can be determined by using vectors to represent both phase and amount of inductive reactance and resistance, or by using the impedance formula.

   a. When using the impedance formula, total impedance can be found by determining the square root of _____ __________ and __________ __________ __________.

b. The impedance of an RL circuit with 3 ohms resistance and 4 ohms inductive reactance is ______ ohms.

10. The amount of power consumed by a purely inductive circuit is practically zero. When current is increasing, inductance converts energy into a magnetic field. When the current is decreasing the magnetic field collapses, returning the energy to the circuit. Energy is borrowed, but none is used. The only power consumed is that which is used by the very small d-c resistance of the inductor.

a. The amount of power consumed by an inductive circuit is practically ________.

11. When a pulse voltage is applied to an RL circuit the length of time required for circuit current to reach 63 percent of maximum is called the time constant. Time constant is determined by dividing the value of R in ohms the value of L in henrys. The resulting waveshapes across R and L are distorted with respect to the pulse input voltage. The inductor voltage is called the differentiated voltage. and the resistor voltage is called the integrated voltage. Five time constants are required for circuit current to reach its maximum value. The universal time constant chart can be used to calculate voltage or current value at any instant of time.

a. The time constant of an RL circuit can be determined by dividing ________ by ________.

b. In an RL circuit the resistor voltage waveform is called the ________ voltage, and the inductor voltage waveform the ________ voltage.

12. The time constant-to-period ratio is a ratio of time duration of the RL circuit to pulse time. This ratio determines the waveshapes of the voltages across both the resistor and the inductor. The most common TC-to-P ratios used are short, very short, extra short, intermediate, long, and very long.

a. The period of a pulse is determined by dividing the ________ of the pulse into 1.

b. All of the input voltage appears across the inductor during the input pulse ________ ________.

13. Capacitance is the property of an electrical circuit that opposes any change in voltage. The capacitor consists of

two conducting plates separated by an insulating material called the dielectric. The two types of capacitors are fixed and variable. A capacitor will block direct current, but will appear to pass alternating current due to the alternate charging and discharging of the capacitor plates. The unit of measurement for capacitors is the farad, although the more commonly used values are microfarad and picofarad (micromicrofarad).

a. The dielectric is the ________ material between the plates of a capacitor.
b. Capacitance is the property that opposes a change in ________.
c. A capacitor is charged when it has the ________ number of electrons.

14. The three factors that affect the value of capacitance are the area of the plates, the separation or distance between the plates, and the type of dielectric material used. The larger the area of the plates, the greater the capacitance; and the smaller the distance between the plates, the greater the capacitance. The higher the dielectric constant of the insulating material between the plate, the greater the capacitance.

    a. If a .01-mfd capacitor has its plate area enlarged three times, its capacitance will be ________ mfd.
    b. If the distance between the plates of a capacitor is doubled capacitance will be ________ its original value.

15. When capacitors are connected in series, parallel, or series-parallel, the methods used to determine total capacitance differ from those used for resistors or inductors. The methods used for determining total parallel resistance or inductance, that is the *like* or the *product-over-sum,* are used to determine total series capacitance. Capacitors add in parallel, as do resistors and inductors in series. With series-parallel connected capacitors the circuit is broken into individual series or parallel branches, then analyzed the same as a resistor or inductor circuit.

    a. If a .05-mfd, a .01-mfd, and a .025-mfd capacitor are connected in parallel, total capacitance will be ________ mfd.

b. If three .03-mfd capacitors are connected in series, total capacitance will be ________ mfd.

16. The relationship between voltage and current in a capacitive circuit is just the opposite of their relationship in the inductive circuit. In a capacitive circuit current leads voltage by 90 degrees. Again, vectors can be used to show this current-voltage relationship.
    a. In a capacitive circuit the vector representation of voltage is shown 90 degrees ________ the current vector.

17. The opposition offered by a capacitor to alternating current is called capacitive reactance, or X_C and it is measured in ohms. Capacitive reactance differs from resistance in that when the frequency of the applied a-c voltage changes, the X_C changes.
    a. If the current in a capacitive circuit is high at a high frequency, and the frequency of the applied voltage is lowered, the current will ________.
    b. The value of X_C depends on the value of capacitance and the ________ of the applied voltage.

18. When an a-c circuit contains both capacitance and resistance, the total opposition to alternating current is called impedance. The total circuit impedance can be determined by using a vector analysis to represent the phase and amount of capacitive reactance and resistance, or by using the impedance formula.
    a. When using the impedance formula, total impedance can be found by determining the square root of ________ ________ and ________ ________.
    b. The impedance of an RL circuit with 9 ohms resistance and 12 ohms X_C is ________ ohms.

19. When a pulse voltage is applied to an RC circuit the length of time required for the capacitor to charge to 63 percent of the applied voltage is called the time constant. The time constant is found by multiplying the value of R in ohms by the value of C in farads. The waveshape of the pulse input voltage appears distorted across R and C. The resistor voltage is called the differentiated voltage, and the capacitor voltage is called the integrated voltage. Five time constants are required for the capacitor to charge to its maximum voltage level, or

for the resistor voltage to drop to its minimum value.

a. The time constant of an RC circuit can be determined by multiplying ________ times ________.

b. In an RC circuit the resistor voltage waveform is called the ________ voltage, and the capacitor voltage the ________ voltage.

20. The time constant-to-period ratio is a ratio of the time duration of the RC circuit to the input pulse voltage time. The TC-to-P ratio determines the waveshape of the voltage across both the resistor and the capacitor. The most common TC-to-P ratios used are extra short, very short, short, intermediate, long, very long.

a. A very long TC-to-P ratio will provide an almost perfect reproduction of the input pulse voltage across the ________.

b. When the leading edge of a pulse voltage is applied to an RC circuit, all of the voltage will appear across the ________.

21. A series LCR circuit, or one that contains resistance, inductance, and capacitance, assumes the characteristic of the predominant reactance. Since X_L and X_C have opposite characteristics, a condition called resonance occurs when the two reactances are equal and cancel each other. The following circuit conditions apply to a series LCR circuit:

1. The circuit acts capacitively at frequencies below resonance, and inductively at frequencies above resonance. At resonance, the circuit is resistive.
2. Circuit impedance is at its maximum value both below and above resonance, but at its minimum value at resonance.
3. Circuit current is at its minimum value both below and above resonance, but at its maximum value at resonance.

a. The only opposition to current in a series LCR circuit at resonance is that offered by the ________.

b. The series resonant circuit that has the greatest amount of current will be the one with the ________ Q or quality.

22. A parallel LCR circuit exhibits properties that are in most respects the opposite of the series LCR circuit. The

following circuit conditions apply to a parallel LCR circuit:

1. The circuit acts capacitively at frequencies below resonance, and inductively at frequencies above resonance. At resonance, the circuit is resistive.
2. Circuit impedance is low at frequencies below and above resonance, but is at its maximum value at resonance.
3. Circuit current is at a high value at frequencies below and above resonance, but at its minimum value at resonance.
4. Loop current, or current within the LC circuit, is minimum at frequencies below and above resonance and maximum at resonance.
   a. Within the loop or LC circuit the impedance at the resonant frequency is ________.
   b. Current to and from the voltage source in a parallel LCR circuit at resonance is at its ________ value.

SUMMARY ANSWERS

1a. The counter emf is generated by an expanding **magnetic field.**

1b. The counter emf **lags** the circuit current by **90** degrees.

2a. A millihenry is **one-thousandth** of a henry.

2b. The unit of measurement for inductance is the **henry.**

3a. If a coil with 50 turns has an inductance of 200 millihenrys, a decrease to 25 turns will lower the inductance to 50 millihenrys.

3b. If a coil with a diameter of .5 inch and in inductance of 1000 millihenrys were doubled in diameter, inductance would increase to **4000** millihenrys.

4a. In an inductive circuit, the voltage **leads** the current by **90** degrees.

4b. When using vectors, the length of each vector represents **magnitude.**

5a. If two inductors connected in series have a total inductance of 650 millihenrys, when L1 is 250 millihenrys, L2 inductance is **400** millihenrys.

5b. If total inductance is lower than the inductor with the lowest value, they are connected in **parallel.**

6a. The amount of X_L of an inductor is dependent on the frequency of the applied a-c voltage and **inductance.**

6b. Inductive reactance is measured in **ohms.**

7a. In a low-pass filter circuit, the inductance is in series with the input-output terminals.

7b. In a high-pass filter circuit, the inductance is in **parallel** with the input-output terminals.

8a. Transformer secondary current will be greater than primary current in a step-**down** transformer.

8b. Transformer secondary voltage will be greater than primary voltage in a step-**up** transformer.

8c. A transformer with five turns on the secondary for every primary turn and with 120 volts applied, will have a secondary voltage of **600** volts.

9a. When using the impedance formula, total impedance can be found by determining the square root of **resistance squared** and **inductive reactance squared.**

9b. The impedance of an RL circuit with 3 ohms resistance and 4 ohms inductive reactance is 5 ohms.

10a. The amount of power consumed by an inductive circuit is practically **zero.**

11a. The time constant of an RL circuit can be determined by dividing L by **R.**

11b. In an RL circuit the resistor voltage waveform is called the **integrated** voltage, and the inductor voltage waveform the **differentiated** voltage.

12a. The period of a pulse is determined by dividing the **frequency** of the pulse into 1.

12b. All of the input voltage appears across the inductor during the input pulse **rise time.**

13a. The dielectric is the **insulating** material between the plates of a capacitor.

13b. Capacitance is the property that opposes a change in **voltage.**

13c. A capacitor is charged when it has the **maximum** number of electrons.

14a. If a .01-mfd capacitor has its plate area enlarged three times its capacitance will be **.03** mfd.

14b. If the distance between the plates of a capacitor is doubled, capacitance will be **one-half** its original value.

15a. If a .05-mfd, a .01 mfd, and a .025 mfd capacitor are connected in parallel, total capacitance will be **.085** mfd.

15b. If three .03-mfd capacitors are connected in series, total capacitance will be **.01** mfd.

16a. In a capacitive circuit the vector representation of voltage is shown 90 degrees **behind** the current vector.

17a. If the current in a capacitive circuit is high at a high frequency, and the frequency of the applied voltage is lowered, the current will **decrease.**

17b. The value of X_C depends on the value of capacitance and the **frequency** of the applied voltage.

18a. When using the impedance formula, total impedance can be found by determining the square root of resist**ance squared** and **X_C squared.**

18b. The impedance of an RL circuit with 9 ohms resistance and 12 ohms X_L is **15** ohms.

19a. The time constant of an RC circuit can be determined by multiplying **R** times C.

19b. In an RC circuit the resistor voltage waveform is called

the **differentiated** voltage, and the capacitor voltage the **integrated** voltage.

20a. A very long TC-to-P ratio will provide an almost perfect reproduction of the input pulse voltage across the **resistor.**

20b. When the leading edge of a pulse voltage is applied to an RC circuit, all of the voltage will appear across the **resistor.**

21a. The only opposition to current in a series LCR circuit at resonance is that offered by the **resistor.**

21b. The series resonant circuit that has the greatest amount of current will be the one with the **highest** Q or quality.

22a. Within the loop or LC circuit the impedance at the resonant frequency is **minimum.**

22b. Current to and from the voltage source in a parallel LCR circuit at resonance is at its **minimum** value.

FINAL TEST

1. The transistor is a ________-controlling device.
   a. voltage
   b. current
   c. power
   d. impedance

2. The nucleus of an atom contains ________ and ________.
   a. protons, electrons
   b. electrons, neutrons
   c. protons, neutrons
   d. photons, neutrons

3. Atoms are electrically neutral when they have the same number of ______ and ______.
   a. protons, electrons
   b. electrons, neutrons
   c. protons, neutrons
   d. photons, neutrons

4. A material through which electrons can pass readily is called a(an) ________.
   a. insulator
   b. field
   c. vacuum
   d. conductor

5. ________ poles of a magnet repel and ________ poles of a magnet attract.
   a. like, unlike
   b. like, like
   c. unlike, unlike
   d. unlike, like

6. A difference in potential is measured in units called ____.
   a. amperes
   b. coulombs
   c. joules
   d. volts

7. A car battery converts ______ energy to ________ energy.
   a. light, electrical
   b. mechanical, electrical
   c. chemical, mechanical
   d. chemical, electrical

8. Maximum current is induced in a wire when it moves at an angle of ________ to the magnetic lines of force.
   a. 0°
   b. 30°
   c. 45°
   d. 90°

9. If the period of a sine wave is 25 μsec, the frequency is ____.
   a. 25kHz
   b. 25MHz
   c. 4kHz
   d. 40kHz

10. The power in a circuit may be found by ________.
    a. $E \times I$
    b. $E \div I$
    c. $E \div R$
    d. $I \times R$

11. A resistor with the following colors: yellow, purple, and green (from left to right) has a value of ________.
    a. 470K
    b. 4.7Meg
    c. 570K
    d. 47Meg

12. The incorrect equation is ____.
    a. $E = I \times R$
    b. $I = E \div R$
    c. $R = E \div I$
    d. $E = I \div R$

13. As the resistance in a circuit is increased the current in a circuit ________.
    a. increases

b. decreases
c. remains the same

14. A resistor whose colors are brown, red, yellow, and silver may have a maximum value of ________.
   a. 144K
   b. 132K
   c. 126K
   d. 13.2K

15. With a current of 2 amperes through a resistance of 12 ohms, the power dissipated is ________.
   a. 24 watts
   b. 3 watts
   c. 48 watts
   d. 288 watts

16. When 12 volts are applied to a circuit whose resistance is 6Kohms the current will be ________.
   a. 2 amperes
   b. 0.2 amperes
   c. 20 ma
   d. 2 ma

17. When 3 μamps flows through an 18Kohm resistor the voltage drop will be ________.
   a. 54 volts
   b. 54 millivolts
   c. 54 microvolts
   d. 6 millivolts

18. When a current of 20 ma is due to a voltage of 40 volts, the resistance in the circuit is ________.
   a. 20K
   b. 2K
   c. 200 ohms
   d. 20 ohms

19. A 12K resistor in series with a 6K resistor results in a total resistance of ________.
   a. 18K
   b. 9K
   c. 6K
   d. 4K

20. The total resistance of a circuit containing a 240-ohm resistor in parallel with an 80-ohm resistor is ________.
   a. 320 ohms
   b. 160 ohms
   c. 60 ohms
   d. 40 ohms

21. Three 15K resistors in parallel result in a resistance of ________.
   a. 45K
   b. 30K
   c. 15K
   d. 5K

22. There are three paths for current at a junction, (paths A, B, and C). If path A supplies 5 ma to the junction, and path B has a current of 8 ma leaving the junction, then path C has a current of ________ ma (entering, leaving) the junction.
   a. 13 ma leaving
   b. 13 ma entering
   c. 3 ma leaving
   d. 3 ma entering

23. A device that offers more impedance to current in one direction than in the other is a (an) ________.
   a. transistor
   b. diode
   c. inductor
   d. capacitor

24. A variable resistor is called a ________.
   a. varactor
   b. variometer

c. potentiometer
d. varistor

25. As the temperature in a resistor is increased, its resistance ________.
a. increases
b. decreases
c. remains the same

26. The resistance of a wire may be increased by (increasing, decreasing) its length and (increasing, decreasing) its cross-sectional area.
a. increasing, increasing
b. increasing, decreasing
c. decreasing, increasing
d. decreasing, decreasing

27. In order to exist in a stable orbit in a given shell an electron must have a certain ____ level.
a. energy
b. valence
c. potential
d. conduction

28. The device whose atomic arrangement falls into the cubic lattice system is the ________.
a. conductor
b. semiconductor
c. insulator
d. inductor

29. The sharing of an electron by adjacent atoms of a semiconductor is known as ________ bonding.
a. covalent
b. valence
c. nuclear
d. atomic

30. A crystal without impurities is known as a (an) ________ crystal.
a. face-centered
b. body-centered
c. ionic
d. intrinsic

31. N-type germanium is formed by doping it with a ________ material.
a. pentavalent
b. tetravalent
c. crystalline
d. ionic

32. When the positive terminal of a battery is connected to the N-type region of a PN junction it is said to be ________.
a. inverted
b. forward-biased
c. reverse-biased
d. diffused

33. The process by which an a-c signal is converted into pulsating direct current is known as ________.
a. amplification
b. rectification
c. inversion
d. conversion

34. A constantly changing current in a wire results in a (an) ________.
a. counter emf
b. inductance
c. conductance
d. voltage

35. The property of a circuit that tends to oppose a change in current is called ________.
a. capacitance
b. resistance
c. conductance
d. inductance

36. The value of an inductor may be increased by (increasing,

decreasing) the number of turns and (increasing, decreasing) the coil diameter.

a. decreasing, decreasing
b. decreasing, increasing
c. increasing, decreasing
d. increasing, increasing

37. In an inductive circuit the current ________ the voltage by ________ degrees.
a. leads, 90
b. leads, 180
c. lags, 90
d. lags, 180

38. The total inductance of a circuit containing a 6-mh inductor in series with a 3-mh inductor is ________.
a. 18 mh
b. 9 mh
c. 3 mh
d. 2 mh

39. The parallel combination of a 36-μh inductor and a 12-μh inductor is equivalent to a ________ inductor.
a. 48-μh
b. 24-μh
c. 9-μh
d. 6-μh

40. The inductive reactance of a circuit may be increased by (increasing, decreasing) its inductance and (increasing, decreasing) the frequency of the applied voltage.
a. increasing, increasing
b. increasing, decreasing
c. decreasing, increasing
d. decreasing, decreasing

41. A device that allows only low frequencies to pass is known as a ________.
a. high-pass filter
b. bandpass filter
c. low-pass filter

42. If 20 volts are applied to the primary of a transformer having a turns ratio of 5:1, the voltage in the secondary will be ________.
a. 100V
b. 20V
c. 4V
d. 1V

43. In a step-up transformer the voltage is (stepped-up, stepped-down) and the current is (stepped-up, stepped-down).
a. stepped-up, stepped-up
b. stepped-up stepped-down
c. stepped-down, stepped-up
d. stepped-down, stepped-down

44. The impedance of a circuit containing a 6-ohm resistor in series with an 8-ohm inductive reactance is ________.
a. 100 ohms,
b. 48 ohms
c. 14 ohms
d. 10 ohms

45. In an RL circuit the time required for the current to reach 63 percent of its maximum value is known as the ________.
a. critical value
b. time constant
c. time factor
d. time vector

46. When a square wave is applied to an LR circuit the waveform across the inductor is ________.
a. integrated
b. differentiated
c. truncated
d. inebriated

47. A device that opposes a change in voltage in a circuit is called a (an) ________.
   a. resistor
   b. capacitor
   c. inductor
   d. transistor

48. A 48-mfd capacitor and a 16-mfd capacitor are connected in parallel, the total capacitance is ________.
   a. 64 mfd
   b. 32 mfd
   c. 24 mfd
   d. 12 mfd

49. Capacitance may be decreased by (decreasing, increasing) the plate area and (decreasing, increasing) the distance between the plates.
   a. decreasing, decreasing
   b. decreasing, increasing
   c. increasing, decreasing
   d. increasing, increasing

50. The capacitive reactance in a circuit may be increased by (increasing, decreasing) the capacitance in the circuit and (increasing, decreasing) the frequency applied to the circuit.
   a. increasing, increasing
   b. increasing, decreasing
   c. decreasing, increasing
   d. decreasing, decreasing

51. A 20-mfd capacitor in series with a 100K resistor results in a time constant of ________.
   a. 20 seconds
   b. 5 seconds
   c. 2 seconds
   d. 0.5 seconds

52. In an RC circuit the current (leads, lags) the voltage by ________ degrees.
   a. leads, 90
   b. leads, 180
   c. lags, 90
   d. lags, 180

53. The voltage across the capacitor in an RC circuit is ________.
   a. integrated
   b. differentiated
   c. desegregated
   d. obliterated

54. The ratio used to determine the shape of a waveform across a component is known as ________.
   a. L-to-R
   b. R-to-C
   c. TC-to-f
   d. TC-to-P

55. In an LCR circuit the total reactance is equal to the ________ X_L and X_C.
   a. sum of
   b. difference between
   c. product of
   d. ratio between

56. In a series-resonant LCR circuit X_L is ________ X_C.
   a. greater than
   b. equal to
   c. less than
   d. in phase with

57. In a series LCR circuit power will be consumed in ________.
   a. L and C only
   b. L only
   c. C only
   d. R only

58. The Q of a resonant circuit is the ratio of ________.
   a. X_L to X_C
   b. X_L to R
   c. X_C to X_L
   d. R to X_C

59. The impedance of a series resonant circuit is ________.
   a. maximum
   b. equal to X_L
   c. equal to X_C
   d. minimum

60. The impedance of a parallel circuit is ________.
   a. maximum
   b. equal to X_L
   c. equal to X_C
   d. minimum

ANSWERS TO FINAL TEST

1.	b	21.	d	41.	c
2.	c	22.	d	42.	c
3.	a	23.	b	43.	b
4.	d	24.	c	44.	d
5.	a	25.	a	45.	b
6.	d	26.	b	46.	b
7.	d	27.	a	47.	b
8.	d	28.	b	48.	a
9.	d	29.	a	49.	b
10.	a	30.	d	50.	d
11.	b	31.	a	51.	c
12.	d	32.	c	52.	a
13.	b	33.	b	53.	a
14.	b	34.	a	54.	d
15.	c	35.	d	55.	b
16.	d	36.	d	56.	b
17.	b	37.	c	57.	d
18.	b	38.	b	58.	b
19.	a	39.	c	59.	d
20.	c	40.	a	60.	a

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